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FLYING QUALITY FACTORS CURRENTLY LIMITING HELICOPTER NAP-OF-THE-EARTH MANEUVERABILITY AS IDENTIFIED BY FLIGHT INVESTIGATION

by Henry L. Kelley, Robert J. Pegg, and Robert A. Champine

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

A flight investigation utilizing two modern lightweight helicopters was conducted to study the effects of flying qualities on nap-of-the-earth maneuver capability. Variation in flying qualities was provided by the markedly different stability and control characteristics which resulted from the basically different rotor systems of the two test vehicles. Several tasks were used to provide a realistic basis on which to determine the parameters most pertinent to maneuver capability.

The results indicate that the initial angular response characteristics about the roll axis and the sensitivity of the height control are of primary importance. For example, the tightness of the initial roll response, as determined by the magnitude of roll-control sensitivity in combination with angular-velocity damping, had a significant influence on the pilot's ability to attain quickly, precisely, and consequently safely, those bank angles necessary to perform the tasks smoothly. Wind velocity and direction, stick-fixed maneuver stability gradients, angular-velocity and control-system coupling, vibration, and power-governing-system characteristics were other factors that significantly influenced the pilot's ability to maneuver the helicopters.

INTRODUCTION

Demands placed on helicopter designers to provide extensive improvements in the maneuver capability of military helicopters are becoming more stringent as evidenced by current Army requirements. Nap-of-the-earth flight techniques and increased vehicle capabilities for the armed-helicopter concept have been evolving over the past several years; however, further work is necessary to aid in establishing satisfactory flying-qualities criteria for future armed helicopters. Armed helicopters and other helicopters which are expected to operate in the nap of the earth should, in general, meet well-known basic criteria such as those found in references 1 and 2, respectively, but in critical areas such as the initial angular response characteristics about the roll axis, special criteria reflecting more stringent requirements should be used. The results of one nap-of-the-earth maneuverability investigation, emphasizing specific criteria which need study, are given in reference 3. Other applicable maneuverability studies are included in references 4 and 5.

A flight investigation utilizing two modern turbine-powered helicopters was recently conducted at the NASA Langley Research Center to determine the effects of flying qualities on the helicopter maneuvering capability in simulated tactical maneuvers. The variation in flying qualities was provided by the markedly different stability and control characteristics which resulted from the basically different rotor systems of the two test vehicles. Several tasks were used to provide a realistic basis on which to determine the parameters pertinent to the maneuver capability. This paper presents time histories of representative maneuver tasks, some basic helicopter stability characteristics critical to the helicopter maneuvering capability, and pertinent pilot comments.

The units for the physical quantities used in this paper are given in both the U.S. Customary Units and in the International System of Units (SI). (See ref. 6.)

APPARATUS

Test Helicopters

Teetering-rotor helicopter.- One of the test helicopters used in this investigation was a turbine-powered vehicle which is representative of the light-observation-class helicopter. This helicopter had a two-bladed teetering-main-rotor system which included a gyro stabilizer bar. Figure 1(a) shows a photograph of the test helicopter, hereinafter called helicopter A, and table I presents a list of its physical characteristics. The normal operating weight during these tests was approximately 2500 pounds force (11 120 N), which corresponds to a hover rotor-blade mean lift coefficient of 0.37 at sea level. Helicopter A was powered by a lightweight 274-shaft-horsepower (204-kW) free-turbine engine which had a fuel control system that included droop compensation for collective pitch inputs, and gas-producer and power-turbine governors. A low-authority rate damping system was available about the three axes but was not used during this investigation. The pilot's cockpit controls included the conventional cyclic stick, rudder pedals, and collective stick, which were powered by an irreversible hydraulic-boost system. Pilot-adjustable friction devices provided control-system forces, but no springs were included to provide control force gradients.

Hingeless-rotor helicopter.- A hingeless-rotor helicopter was used during this investigation to provide comparisons between helicopters with basically different rotor systems and hence different control response and stability characteristics. The three stainless-steel main-rotor blades were cantilevered at the hub instead of being hinged or gimbaled; however, the blades were mounted on bearings about the feathering axis. Figure 1(b) shows a photograph of the test helicopter hereinafter called helicopter B, and table II presents a list of its physical characteristics. The operating weight during this investigation was about 4100 pounds force (18 237 N) which corresponds to a hover rotor-blade mean lift coefficient of 0.43 at sea level. Power was supplied by a 550-shaft-horsepower (410-kW) free-turbine engine, the output of which is controlled and governed in basically the same way as helicopter A, except that it does not have the collective droop compensation on the power-turbine governing system. The cyclic and collective controls in the pilot's cockpit were operated through an irreversible power-boost system. The rudder pedals were not power-boosted. The longitudinal control feel system included a spring, a damper, a bobweight, and a dynamic-pressure sensor. This sensor was not used during this investigation. The lateral and directional controls used springs to provide control force gradients and the forces could be trimmed to zero by the pilot through an electrically operated trim system. The collective stick incorporated the usual friction device and a centering spring to provide the pilot with satisfactory control force characteristics. Trim was not available on the collective control. A detailed description of the control system may be found in reference 7.

Instrumentation

In general, the instrumentation used on helicopters A and B consisted of standard NASA sensing and recording equipment. Parameters recorded, which were pertinent to this investigation, were engine shaft horsepower, airspeed, sideslip angle, the pilots' control positions, translational accelerations along the three axes, and angular velocities about the three axes. Photographs showing most of the sensing and recording equipment for the two vehicles are presented in figure 2. The recording equipment was located just behind the pilot and copilot seats on both helicopters. More extensive instrumentation was utilized, especially the stress measuring equipment on helicopter B; however, details of this instrumentation are not given because the stress results have been given only a brief qualitative treatment herein. A detailed discussion of the stress results is presented in reference 8.

DESCRIPTION OF TASKS

The purpose of the tasks used during this investigation was to provide a quantitative and qualitative basis on which to evaluate the parameters most pertinent to the maneuver capability of the test helicopters. Most of the tasks originated from experience gained from military tactics. One of the tasks, however, the slalom course, was devised at the Langley Research Center to provide a highly demanding and repeatable task wherein an overall assessment of vehicle maneuverability could be made. The specific problem areas were usually investigated separately with the less demanding maneuver tasks. However, if significant changes were made to the vehicle, such as locking out the collective control, the more demanding tasks could then be repeated to understand better the particular problem affecting maneuverability. For most cases the tasks were flown at a height above the ground of approximately 50 feet (15.24 m) or less. Although six tasks were investigated quantitatively, this paper presents quantitative results from only the slalom course and the teardrop turn; the other four tasks were either a part of the slalom and teardrop-turn tasks or were determined from data and pilot comment not to be limited by the helicopter. Figure 3 presents a graphic illustration of the six tasks. A description of the tasks is given subsequently herein. Except for the slalom task, the names used for these tasks are consistent with Army terminology for the maneuvers described.

These tasks, especially the slalom task, were not necessarily intended to duplicate the maneuvers used by helicopters during nap-of-the-earth operations. In order to obtain the most effective pilot-helicopter system, the designer must strive to provide the pilot with a helicopter, wherein the pilot is the limiting factor in the operation and not the helicopter. Therefore, repetitive tasks of sufficient difficulty must be utilized to point out characteristics in the helicopter that are limiting the pilot.

Slalom Course

This slalom maneuver course, requiring rapid and sustained maneuvering, was devised to provide a task for assessment of overall vehicle maneuver capability. The course, as utilized during this investigation, consisted of six easily visible ground markers approximately 4 feet (1.22 m) high laid out in a straight line. The distance between each marker was chosen as a function of the test speed of the vehicles, and for this investigation the distance between each marker was 400 feet (121.92 m) (airspeed in the course between 60 and 80 knots) and 200 feet (60.96 m) (airspeed in the course between 30 and 40 knots). The pilot started the course in two ways. First, a start from hovering flight was made in line with the markers at a distance from the first marker equal to the marker spacing. Second, a running type of start was made whereby the pilot approached the course in line with the markers at the highest possible airspeed so that the pilot was assured that he would not overrun any of the ground markers. Ideally, this task would be performed by using coordinated banked turns. The steepness of the bank angle would be determined by the capability of the pilot-helicopter system with an upper limit of 90°. The test vehicles were flown at the lowest feasible height above the ground. For these tests, where airspeeds were less than 80 knots, the pilot was able to hold the height above the ground to less than 50 feet (15.24 m). Also, in performing this task, the pilot treated each marker as if it were higher; that is, the vehicle was maneuvered so that the rotor disk missed the imaginary vertical line extending from the markers.

Teardrop Turn

The teardrop turn is a return-to-target-type maneuver. The vehicles were flown at low altitude over a marker (target) on the ground after which the pilot executed a maximum-performance turn in either direction to get back to the target in the shortest length of time. Also, the pilot attempted to hold the helicopter at a constant altitude. Several airspeeds were used. This maneuver was performed at low altitude without climbing, theoretically to take advantage of terrain cover. Rollout is made in sufficient time to allow 3 or 4 seconds to use forward-firing fixed guns at the target. A time delay in starting the turn after first passing over the target is necessary later to provide the 3 or 4 seconds of fuselage-level steady flight which is required for accurate delivery of ordnance.

S-Turn

The S-turn is a terrain-avoidance-type maneuver which involves a rapid rolling turn in one direction to change heading by 90°, followed by another rapid rolling turn in the opposite direction to return the vehicle to the original heading. Airspeeds used to enter this maneuver varied from 25 knots to 60 knots. The S-turn is therefore a lateral sidestep maneuver.

Hit-the-Deck

The hit-the-deck maneuver is designed to get the helicopter rapidly from a low-altitude cruise position into the nap of the earth. Upon starting from cruise flight at about 500 feet (152.40 m) above the terrain, a maximum-performance maneuver is executed by the pilot to get the vehicle close to the ground in the shortest time feasible. The primary controls used are the longitudinal cyclic stick and the collective stick.

Scramble

The scramble is a maximum-performance accelerating transition starting from hovering flight close to the ground. Throughout the transition the vehicle is kept as close to the ground as deemed feasible by the pilot.

Whoa-Boy

The whoa-boy is a lateral quick-stop maneuver and is designed to allow the pilot to make a quick stop in the nap of the earth without gaining appreciable altitude. Also, the lateral flare permits improved ground visibility for the pilot.

RESULTS AND DISCUSSION

Initial angular response characteristics were found to have a significant influence on the pilots' ability to maneuver, particularly about the roll axis. (Initial angular response, as used in this paper, is defined as the initial shape of the angular-velocity time history after a control input has been made.) Maneuvers in which the different roll angular response characteristics were the most critical were those which required banking to make large and rapid heading changes.

Rolling Characteristics

Analysis of the time histories from various tasks together with the pilots' comments indicated three characteristics of the roll control to be of importance. These characteristics are as follows:

(1) Roll-control power, or total angular-acceleration capability from trim ($\mathrm{rad/sec^2}$)

(2) The initial shape (tightness) of the angular response, as determined by the magnitude of the control sensitivity $\left(\frac{\mathrm{rad/sec^2}}{\text{Unit control deflection}}\right)$ in combination with the angular-velocity damping $\left(\frac{\mathrm{rad/sec^2}}{\mathrm{rad/sec}}\right)$

(3) A combination of characteristics which causes pilots to comment that roll-and-turn capability of all helicopters tested is consistently better when rolling maneuvers are performed to the right

These three characteristics are discussed in detail subsequently.

Roll-control power.- The maximum available rolling velocity, which is determined by the roll-control power in combination with the angular-velocity damping, was approached during extreme maneuvers. For instance, flight records and pilot comment indicated that roll-control stops were struck when the test helicopters were maneuvered through the slalom course. Stop-striking with the stick was noted particularly with helicopter A, even though it had more than a conventional magnitude of roll-control power available (about 2.30 $\mathrm{rad/sec^2}$). The minimum values of roll-control power required to meet the Visual Flight Rules (VFR) for this size helicopter are 1.24 $\mathrm{rad/sec^2}$ (derived from ref. 1) and 1.94 $\mathrm{rad/sec^2}$ (derived from ref. 2).

Helicopter B had a large amount of control power (approximately 5.30 $\mathrm{rad/sec^2}$) when compared to the minimum amount required for it to meet the VFR roll-control specifications. These values are 0.97 and 1.38 $\mathrm{rad/sec^2}$ derived from references 1 and 2, respectively. For helicopter B the pilot reported that during the slalom course with markers spaced at 400-foot (121.92-m) intervals, no roll-control stop striking was encountered. Flight records show that this observation was substantially correct, with only an occasional momentary control strike occurring. However, when the slalom course with the 200-foot (60.96-m) marker spacing was attempted, the amount of time spent on the roll-control stops and the frequency of the stop strikes were considerably increased. The roll-control power (initial angular acceleration) is believed to be adequate, and the lateral control stop contact probably reflects a need for more angular-velocity capability which would enable the pilot to reach more quickly a given bank angle after a lateral control input has been made.

Initial shape of angular response.- The initial shape (tightness) of the angular response, as determined by the magnitude of control sensitivity $\left(\frac{\text{rad/sec}^2}{\text{Unit control deflection}}\right)$ in combination with angular-velocity damping $\left(\frac{\text{rad/sec}^2}{\text{rad/sec}}\right)$, had a significant influence on the pilots' ability to attain quickly and precisely the bank angles necessary to perform the tasks smoothly. The pilots' comments indicated that the tighter response provided by the hingeless-rotor system of helicopter B provides greater maneuver capability in most respects.

Approximate values of control power, control sensitivity, and angular-velocity damping for helicopters A and B are presented in table III for the roll axis. These values were obtained from time histories of step control inputs recorded during hovering flight. Table III also presents the minimum requirements for these angular rolling response characteristics as specified in references 1 and 2. The maximum attainable angular rolling velocity of helicopters A and B in forward flight was about 1.0 rad/sec and 0.7 rad/sec, respectively. A basic treatment of the initial angular response characteristics provided by the hingeless-rotor system is included in reference 9.

Comparison of right and left roll-and-turn capability.- As previously mentioned, pilots have commented that the roll-and-turn capability of all helicopters tested is consistently better when rolling maneuvers are performed to the right. The characteristic or combination of characteristics which could produce this effect are not completely understood at this time. A thorough understanding of this effect would probably involve lengthy mathematical analyses. However, several possible factors (either self-explanatory or explained in subsequent sections) which could be expected to contribute to this effect are as follows:

(1) Cyclic trim required of the main rotor because of the forward speed of the vehicles

(2) Changes in lateral flapping of the main rotor, such as those which are known to result from changes in normal acceleration

(3) Asymmetric adverse yaw

The following factors are believed to be compounding causes which could influence this effect:

(1) Control cross coupling

(2) Collective sensitivity

(3) Induced cyclic inputs due to normal acceleration (linkage effects)

General Problems in Slalom Course

The slalom task was used for qualitative assessment of vehicle maneuver capability as well as to study the effects of specific maneuver characteristics or problems in some detail. For example, time histories of many of the pertinent parameters of helicopter A as it maneuvered through the slalom course with 400-foot (121.92-m) marker spacing are shown in figure 4. Examination of the time histories of the control positions and related angular velocities confirms that the roll axis is the most demanding because the lateral stick is close to the stop several times throughout the run. Also, near-maximum rolling angular-velocity capability of about 1.0 rad/sec was used. This time history is presented because of the good control coordination reported by the pilot. As another example of the severity of this task, the performance of an H-13G helicopter was limited by the gyro stabilizer bar contacting dynamic stops. The H-13G, which is a time-proven training and utility helicopter, was used for task evaluation and development during early phases of the investigation.

Helicopter A.- Pilot comments and observations were noted when performing the slalom task with both the 200-foot (60.96-m) marker spacing and the 400-foot (121.92-m) marker spacing. First, for the slalom task with the 200-foot (60.96-m) marker spacing, wherein the maximum airspeed reached was about 40 knots and the height above the ground did not exceed 30 feet (9.14 m), pilot comments and observations were as follows:

(1) The left lateral control stop was contacted occasionally.

(2) Sideslip angle was difficult to control.

(3) The rolling angular-velocity damping appeared to be too low.

(4) Occasional main-rotor blade-stop pounding occurred.

Second, during flights through the slalom course with 400-foot (121.92-m) marker spacing, pilot comment indicated that the left lateral control stop was contacted; however, the time spent on the control stops and the frequency of stop contact were reduced from those encountered during the 200-foot (60.96-m) marker spacing. (These and other comments on the stick stop striking were derived from other numerous analyzed records rather than the sample time histories presented in this paper.)

Helicopter B.- Figure 5 presents time histories of preliminary trials of helicopter B maneuvering through the slalom course with 400-foot (121.92-m) marker spacing. Examination of some of these relatively erratic time histories shows that problems existed during this maneuver that prevented satisfactory control coordination and smoothness of operation. The time histories from the other tasks flown with this helicopter were much less erratic. One factor that contributed to the lack-of-coordination problem, adverse yaw, was already known to exist. The adverse-yaw characteristics are discussed subsequently.

Further investigations were directed toward determining the parameters contributing most to the lack-of-coordination problem. Several factors were found to be probable causes. For instance, it was known that the height control (collective-stick control) was too sensitive. Measurements obtained from time histories of step collective inputs indicated sensitivities between 0.4 and 0.6g/inch (0.158 to 0.236g/cm) with initial peaks of 0.8g/inch (0.315g/cm). (The numerical equivalent of 1g is 9.81 m/sec^2.) Although the collective sensitivity was not considered by the pilots to be the main factor contributing to the coordination problem, these values are far outside the range of desirable values (0.1 to 0.2g/inch (0.039 to 0.079g/cm)) established by a recent height-control investigation (ref. 10). At least some of the collective-control sensitivity can be attributed to the particular design of the collective control of this helicopter. When compared with more conventional helicopters, this design requires approximately 50 percent less pilot hand movement on the collective-control stick per degree of collective pitch-angle change.

In an effort to measure what effect the sensitive collective control had on the problems encountered on the slalom course, the task was repeated with the collective control fixed. The results are presented as time histories in figure 6. In the interest of safety this run was made at a height above the ground of about 75 feet (22.86 m). Also, no ground markers were used to provide a positive ground track; however, the pilot did perform a series of near-maximum-effort roll reversals, wherein coupling was the limiting factor as reported by the pilot. Although the maneuver shown in figure 6 was performed in a somewhat different manner than that shown in figure 5, the improvement in pilot coordination and trace smoothness does indicate that the collective control was too sensitive and probably was contributing to the overall pilot coordination problem. Also, the time histories in figure 6 show that more roll reversals were attained per unit time and at a generally higher airspeed, thereby indicating that the aircraft characteristics were not as limiting as before.

Another control-linkage factor that seems to be contributing to the coordination problem is the swashplate motion induced by the vertical motion of the spring-suspended cockpit. Measurements of swashplate motion per g unit indicate an equivalent 0.83 inch of longitudinal stick movement (2.1 cm of longitudinal stick movement) and 0.50 inch of lateral stick movement (1.27 cm of lateral stick movement). The equivalent longitudinal control motion per g unit is unstable in that it is rearward with an increased normal acceleration, and thereby further increases the normal acceleration. Moreover, the normal acceleration added by collective pitch can produce additional acceleration (part of which is almost instantaneous) by reason of the cab-deflection effect on longitudinal control.

An additional factor tending to complicate the coordination problem was an unbalanced collective pitch-control stick. The fully boosted collective stick incorporated a friction device and a centering spring. During variations in vertical acceleration, as were typically encountered in the slalom maneuvers, the collective-stick force was out of phase with the aircraft vertical acceleration. The out-of-phase force can lead to pilot-induced vertical oscillation of the helicopter. This factor appears more critical in combination with the longitudinal control coupling with vertical acceleration.

In order to eliminate the undesired control system coupling with cab motion, the cab was rigidly fixed to the fuselage. Also, in order to eliminate a down collective force with positive vertical acceleration, the collective stick was mass-balanced to give zero collective force with vertical acceleration.

A repeat of the 400-foot- (121.92-m-) marker slalom task was made to investigate the effects of the modifications on the pilot's control coordination difficulties. Pilot comment indicated that maintaining proper control coordination was not difficult and that the overall task was easier to accomplish with the cab rigidly fixed to the fuselage. Also, with the collective control balanced, the pilot noted that very little collective-control jockeying was required. A rather severe vertical jerk occurring once in each revolution (but not sinusoidal) was reported by the pilot during sustained banked turns of approximately 1.3 to 1.4 vertical g units at airspeeds of 35 to 40 knots. During the slalom tasks these jerks were not encountered; however, the possibility of these encounters caused the pilot to be cautious and apprehensive and was considered to be the limiting factor. The jerk was subsequently associated with stop contacts of the transmission isolation system.

A time history of one run is presented in figure 7. The less erratic time histories and smaller sideslip angles developed indicate that the pilot's control coordination was much improved when compared with that encountered during the run illustrated in figure 5.

Maneuver Stability

During maneuver tasks that required sustained high normal acceleration, such as the teardrop turn, the variation of stick-fixed maneuver stability with normal acceleration appeared to be a potential problem. The pilots flying helicopter A reported a definite searching (movement of control stick in search of trim position) at the peak normal accelerations with the longitudinal stick which seemed to them to represent angle-of-attack instability when performing teardrop-turn maneuvers. Although the time history of the longitudinal stick position in figure 8 shows more apparent searching amplitude at 1.0g flight, it was not considered objectionable by the pilot, perhaps because of the lower frequency. A study of the basic maneuver stability characteristics of helicopter A was made to gain a better understanding of the problem and its effect on flying qualities during maneuvering flight. Figure 9 presents the stick-fixed maneuver stability characteristics of this helicopter at four trim-level-flight airspeeds. These data were obtained by using a windup-turn technique. The results indicate generally stable maneuver stability for each of four airspeeds. The maneuvering stability becomes more nearly neutral with increasing airspeed and, in some cases, the data at the higher load factors indicate neutral or slightly unstable gradients. The pilot described the maneuver stability to be neutral to unstable at the higher load factors. The main-rotor angle-of-attack contribution to the instability problem probably became predominant at the higher normal load factors, although nonlinear fuselage moment characteristics could have contributed also. One possible solution to this problem would be the use of a larger horizontal stabilizer to offset further the rotor contribution.

Wind Effects

Under the moderate wind conditions experienced during this investigation, no important differences in flying qualities due to wind effect were noted by the pilots for the differences in parameters represented by helicopters A and B. However, the pilots repeatedly stated that they strongly preferred to perform the tasks when changes in the vehicle flight path close to the ground could be made into the wind. The classic downwind-turn piloting problem seems to have been amplified by the relatively low airspeeds involved in performing maneuvers close to the ground, although the winds during these tests were usually less than 20 knots. Also, the overall maneuver capability of the test helicopters is generally reduced under adverse wind conditions since the pilot tends to allow margins on important maneuver parameters, such as control travel, normal acceleration, and installed power, in order to handle the uncertain wind effects safely.

Other Considerations

Vibration.- The increase in cockpit vibration levels associated with high vertical-acceleration maneuver tasks reduced the pilot's capability to perform these maneuvers satisfactorily. The piloting technique also had an effect on the vibration levels. Analysis of stress and vibration data, obtained from helicopter B, indicated that the alternating stress levels and hence the overall vehicle vibration were reduced following a reduction in sideslip angles reached in the turns. The mean stress levels were not noticeably affected by this improvement, however. A basic treatment of the loads encountered by a helicopter hingeless-rotor system, including maneuvers, is given in references 8 and 11.

Coupling.- Pitch-due-to-roll and roll-due-to-pitch angular-velocity cross coupling, although noticeable to the pilots, did not seem to be a clear-cut problem with either of the test helicopters during this investigation. Coupling became most apparent during the slalom-course task; however, it was difficult to assess what effect it may have had on this task.

The most objectionable coupling experienced during the slalom task was the adverse yaw experienced on helicopter B. Adverse yaw is usually associated with fixed-wing aircraft and has not been previously considered a problem with single-rotor helicopters. The exact contributions of helicopter adverse yaw in a hover have not been firmly determined, but a large contributing source in forward flight seems to come from the variation of rotor-induced power with the aircraft rolling velocity. Consequently, this objectionable characteristic is felt during maneuvers, such as the slalom task, where high roll rates are required. Figure 10 shows a time history of the adverse-yaw characteristics of helicopter B after a step roll-control input has been made in hovering flight with rudder pedals fixed. The data show that the adverse-yawing angular velocity starts at approximately maximum rolling velocity in both left and right rolls. Pilots report that the adverse yaw is more severe when rolling to the left and that the yaw angle decreases with increasing speed.

Power governing systems.- During this investigation the pilots noted that the characteristics of the turbine-engine governing systems on helicopters A and B imposed operational limitations on maneuver capability in the nap of the earth because of the large power variations. Torque and/or turbine inlet temperature limits can be exceeded when operating at high gross weight or under stringent density altitude conditions.

When performing maneuver tasks close to the ground (within one rotor diameter at times), the full attention of the pilot is required outside the cockpit to maintain a safe ground clearance. The maneuvers requiring high normal load factors, such as the teardrop turn and hit-the-deck, seem to offer the biggest power-governing problem. As an example, a step-by-step description of how the conventional-power governing systems can be a problem is illustrated for the teardrop turn. The pilot enters a relatively high vertical-acceleration turn in a trim condition with respect to speed and collective-pitch setting (power) wherein the governor initially checks the overspeed of the main rotor due to autorotative tendencies by reducing engine-horsepower output. A reduction in engine power by the governing system is in the opposite direction from that required to help maintain the original trim airspeed in a banked turn. Therefore, in order to maintain constant airspeed through the turn, additional power must be added by the pilot to offset the power reduced by the governor and to maintain the airspeed that would normally be lost as a result of the normal acceleration used in the maneuver. After rolling out of the turn, the pilot has a high collective setting for the trim-level-flight airspeed and, most important, the reduction in normal load factor causes the rotor rotational speed to decrease which the governor offsets by adding more fuel and power. Temperature or torque limits may well be exceeded. Therefore, when the pilot's attention is required outside the cockpit, maneuver capability is reduced and the engine-power-system limitations can inadvertently be exceeded.

The lack of a tight governor system with regard to main-rotor rotational speed may contribute to an increase in pilot workload. For example, for helicopter B, although the static rotor-speed droop from minimum power to maximum power was from 104 percent to 100 percent of the normal rotor speed, the transient droop measured was much larger. For power transient extremes, such as those encountered in the scramble and the whoa-boy, the rotor-speed extremes reached 96 percent and 108 percent of the normal rotor speed, respectively. The rotor-speed variation during the slalom task was from 98 percent to 106 percent. These transients closely approach the maximum allowable rotor rotational speed, which requires pilot attention and tends to limit the maneuver capability.

Main-rotor rotational speed, as such, can also be a problem for the parts of those maneuvers when the pilot uses cyclic control to arrest the rate of descent near the ground where an autorotative flight condition might be entered with an attendant increase in rotational speed. Because at such a time strict attention is required outside the cockpit, an increase in the allowable main-rotor rotational-speed limits would help to alleviate the pilot's problems in a cyclic-control maneuver of this type.

CONCLUSIONS

A flight-test investigation utilizing two modern lightweight turbine-powered helicopters has been conducted to study the effects of flying qualities on helicopter maneuver capability in a nap-of-the-earth environment. Variation in flying qualities was provided by the markedly different stability and control characteristics which resulted from the basically different rotor systems of the two primary test vehicles. Several different maneuver tasks were used. On the basis of the results obtained from this investigation, the following conclusions are drawn:

1. The initial angular response characteristics, particularly about the roll axis, had a significant influence on the pilot's ability to maneuver the test helicopters. In most cases, the tightness of the roll response characteristics of one of the test helicopters, as produced by the magnitude of control sensitivity in combination with angular-velocity damping, provided the pilots with greater overall capability to perform maneuvers with

precision, even though the maximum angular velocity available was less than that for the helicopter with a lower sensitivity.

2. Roll-control-stop contact, which usually indicates that the roll-control power is inadequate, was one limiting factor experienced by both helicopters; however the roll-control power of the helicopter with the hingeless rotor is believed to be adequate and the control-stop contact probably reflects a need for more angular-velocity capability which would enable the pilot to reach a given bank angle more quickly. Less than half the roll-control-stop contact was noted for the helicopter with the tighter roll response when the helicopters were maneuvered through a slalom course with the 400-foot (121.92-m) markers.

3. When unstable stick-fixed maneuver stability gradients existed, the maneuver capability was adversely affected during sustained high vertical-acceleration maneuver tasks.

4. Wind velocity and direction had a significant effect on the pilot's capability to maneuver the helicopters. The classic downwind-turn piloting problem seems to have been amplified by the relatively low airspeeds involved in performing maneuvers close to the ground.

5. Height-control sensitivities between 0.4 and 0.6g/inch (0.158 to 0.236g/cm) with initial peaks to 0.8g/inch (0.315g/cm) adversely affected pilot capability to coordinate the various tasks, especially the slalom course. The height-control sensitivity values are far outside the range of desirable values (0.1 to 0.2g/inch (0.0394 to 0.0788g/cm)) established by a recent height-control investigation.

6. Pitch-due-to-roll and roll-due-to-pitch angular-velocity cross coupling, although noticeable to the pilots, did not seem to be unsatisfactory to them. The adverse yaw present, in one of the test helicopters, was considered to be clearly unsatisfactory by the pilots.

7. The characteristics of the engine governing systems, and the allowable main-rotor rotational-speed limits, tended to impose operational limits on maneuver capability.

Langley Research Center,
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TABLE I.- PHYSICAL CHARACTERISTICS OF HELICOPTER A

Main rotor:	
Diameter, ft (m)	33.33 (10.16)
Number of blades	2
Blade chord, in. (cm)	13 (33.02)
Airfoil section	Modified NACA 0011 (drooped leading edge)
Twist, deg	-10
Flapping angle, deg	±4.5
Blade taper ratio	1
Blade area, ft^2 (m^2)	36.1 (3.35)
Disk area, ft^2 (m^2)	873 (81.10)
Solidity	0.0414
Tip speed, ft/sec (m/sec)	689 (210)
Normal operating speed, rpm	394
Tail rotor:	
Diameter, ft (m)	5.17 (1.58)
Number of blades	2
Blade chord, in. (cm)	5.25 (13.34)
Airfoil section	BHC-TAD-S_2
Twist, deg	0
Blade taper ratio	1
Blade area, ft^2 (m^2)	2.26 (0.21)
Disk area, ft^2 (m^2)	21.0 (1.95)
Solidity	0.108
Normal operating speed, rpm	2553
General:	
Normal weight, lbf (N)	2500 (11 120)
Empty weight, lbf (N)	1500 (6672)
Overload gross weight, lbf (N)	2900 (12 899)
Overall length, ft (m)	30.08 (9.17)
Overall height, ft (m)	8.83 (2.69)
Landing-gear tread, ft (m)	6.58 (2.01)
Power (Allison T63-A-5), hp (kW)	274 (204)
Maximum-level-flight airspeed, knots	115
Gear ratios:	
Power turbine to engine output shaft	5.833:1
Engine output shaft to rotor	15.23:1
Engine output shaft to tail rotor	2.35:1
Center of gravity (fuselage station)	103.8
Moments of inertia:	
Roll, slug-ft^2 (kg-m^2)	340 (461)
Pitch, slug-ft^2 (kg-m^2)	1550 (2101)
Yaw, slug-ft^2 (kg-m^2)	1300 (1763)
Total control travels (from grip centers):	
Lateral stick, in. (cm)	9.3 (23.62)
Longitudinal stick, in. (cm)	11.0 (27.94)
Pedals, in. (cm)	5.05 (12.83)
Collective stick, in. (cm)	10.7 (27.18)

TABLE II.- PHYSICAL CHARACTERISTICS OF HELICOPTER B

Main rotor:	
Diameter, ft (m)	35 (10.67)
Number of blades	3
Blade chord, in. (cm)	13.5 (34.29)
Airfoil section	NACA 0012
Twist, deg	-5
Blade taper ratio	1
Blade area, ft^2 (m^2)	57 (5.30)
Disk area, ft^2 (m^2)	962 (89.37)
Solidity	0.0591
Tip speed, ft/sec (m/sec)	650 (198.1)
Normal operating speed, rpm	355
Tail rotor:	
Diameter, ft (m)	6 (1.83)
Number of blades	2
Blade chord, in. (cm)	8.5 (21.59)
Airfoil section	NACA 0012
Twist, deg	-4.4
Blade taper ratio	1
Blade area, ft^2 (m^2)	2.83 (0.26)
Disk area, ft^2 (m^2)	23.75 (2.21)
Solidity	0.164
Normal operating speed, rpm	2085
General:	
Normal weight, lbf (N)	3500 (15 568)
Empty weight, lbf (N)	2650 (11 787)
Overload gross weight, lbf (N)	4100 (18 236)
Overall length, ft (m)	42 (12.80)
Overall height, ft (m)	8 (2.44)
Landing-gear tread, ft (m)	6 (1.83)
Power (PT6B-9), hp (kW)	550 (410)
Maximum level-flight airspeed, knots	157
Gear ratios:	
Power turbine to engine output shaft	5.3:1
Engine output shaft to main rotor	17.55:1
Engine output shaft to tail rotor	2.985:1
Moments of inertia (for aircraft weight = 3500 lbf (15 568 N)):	
Roll, slug-ft^2 (kg-m^2)	850 (1152)
Pitch, slug-ft^2 (kg-m^2)	2530 (3430)
Yaw, slug-ft^2 (kg-m^2)	2410 (3267)
Total control travels (from grip centers):	
Lateral stick, in. (cm)	5.5 (13.97)
Longitudinal stick, in. (cm)	10.0 (25.40)
Pedals, in. (cm)	6.5 (16.51)
Collective stick, in. (cm)	8.6 (21.84)

TABLE III.- HOVERING ROLL-CONTROL CHARACTERISTICS

OF HELICOPTERS A AND B

[Weight of helicopter A, 2500 lbf (11 120 N);
weight of helicopter B, 4100 lbf (18 237 N)]

Source	Helicopter	Initial response characteristics			
		Sensitivity		Damping/Inertia,	Control power,
		$\frac{\text{rad/sec}^2}{\text{in.}}$	$\frac{\text{rad/sec}^2}{\text{cm}}$	$\frac{\text{rad/sec}^2}{\text{rad/sec}}$	$\frac{\text{rad}}{\text{sec}^2}$
Measured data	A	0.50	0.20	-3.00	2.30
	B	1.93	.76	*-8.00	5.30
Criteria (ref. 2)	A	0.65	0.26	-4.34	1.94
	B	.46	.18	*-3.15	1.38
Specification requirements for instrument flight (ref. 1)	A	0.54	0.21	-4.34	1.61
	B	.42	.17	*-3.15	1.25
Specification requirements for visual flight (ref. 1)	A	0.41	0.16	-3.13	1.24
	B	.32	.13	*-2.27	.97

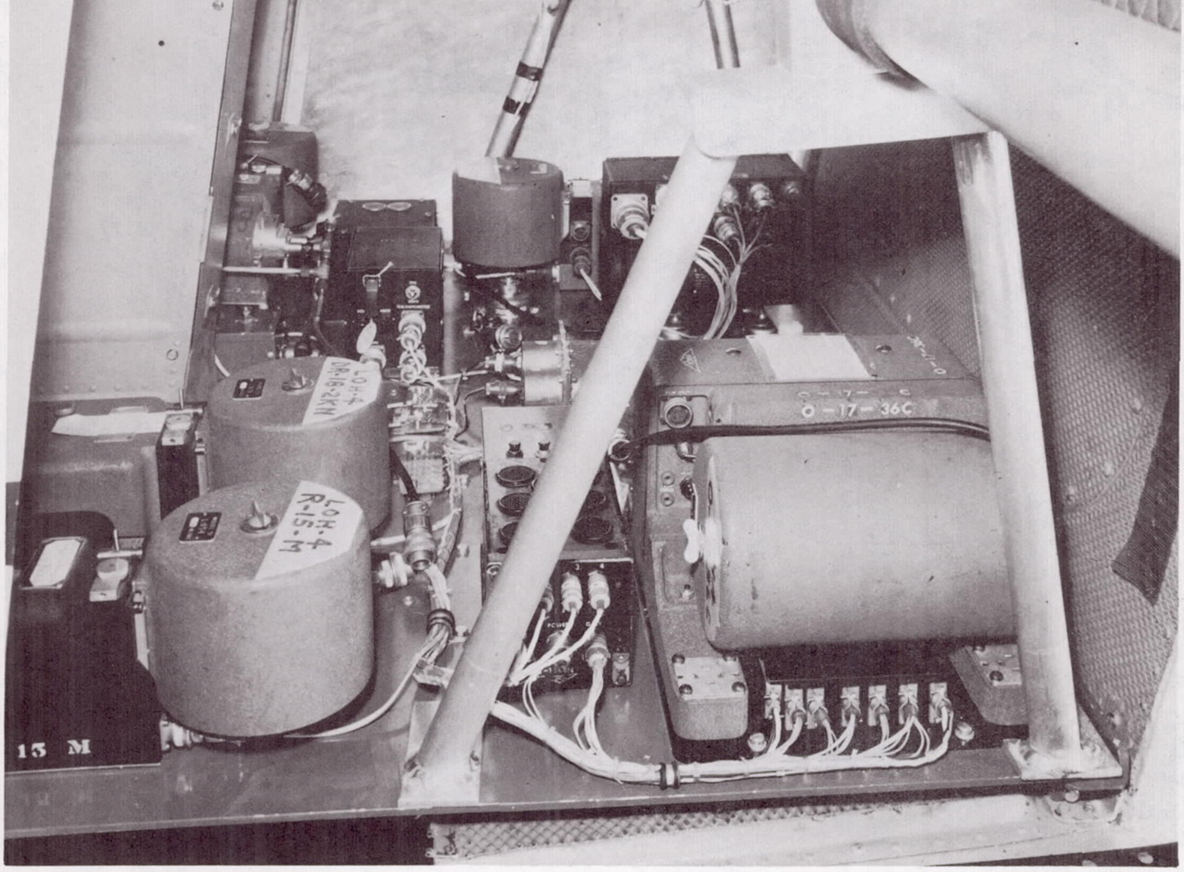
*Effective value for control inputs.

(a) Turbine-powered teetering-rotor helicopter (helicopter A). L-65-5219

Figure 1.- Test helicopters.

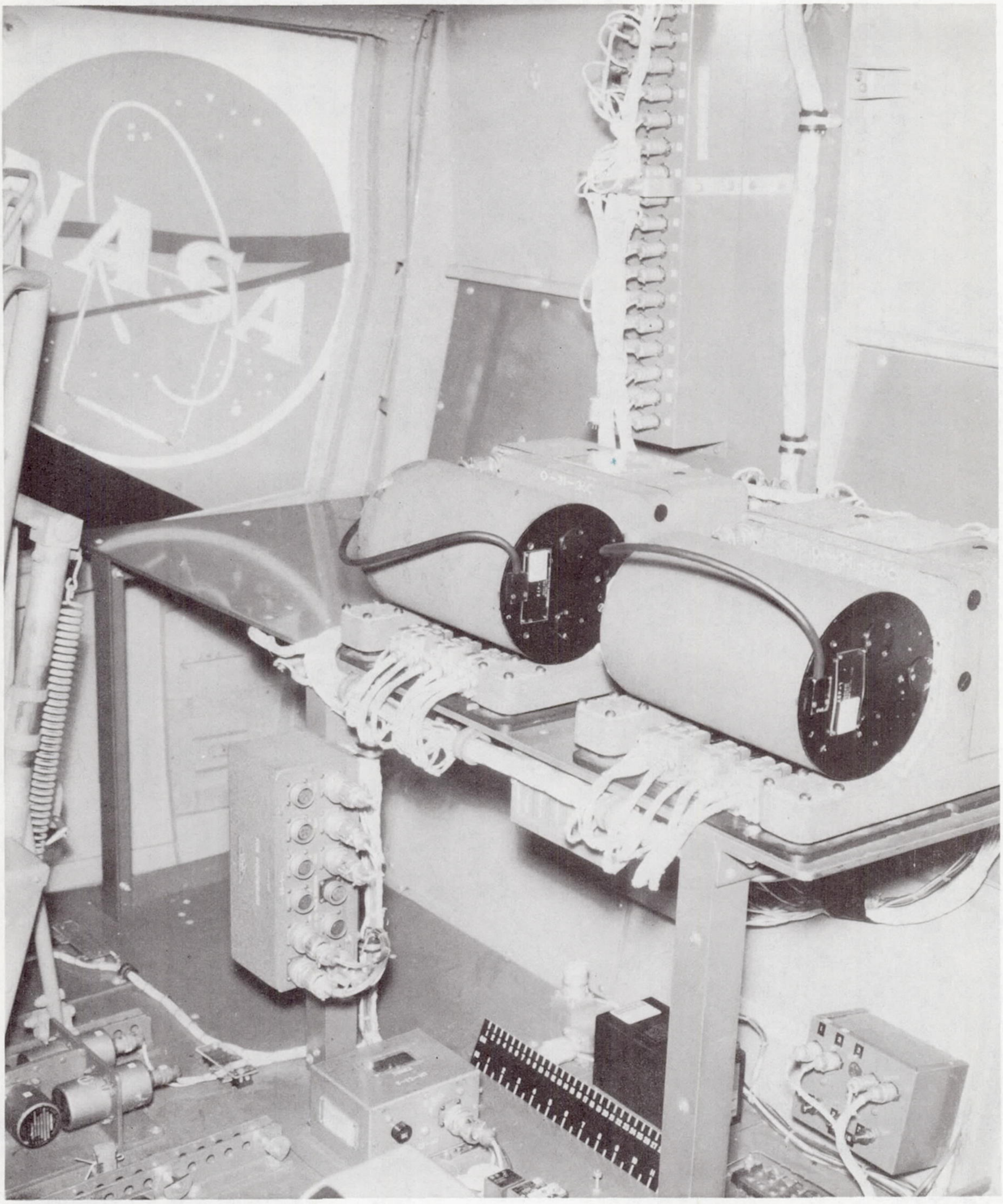
(b) Turbine-powered hingeless-rotor helicopter (helicopter B). L-65-5468

Figure 1.- Concluded.



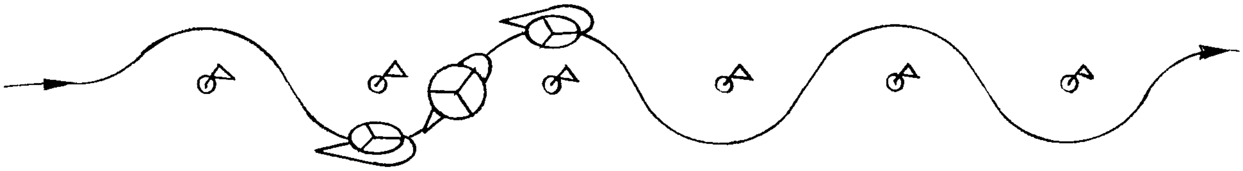
(a) Helicopter A. L-66-4845

Figure 2.- View of sensing and recording instrumentation located behind pilot and copilot seats.

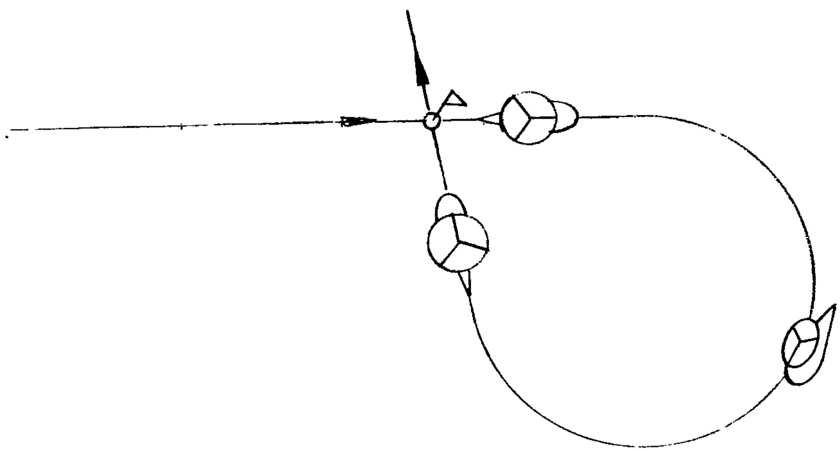


(b) Helicopter B. L-65-8270

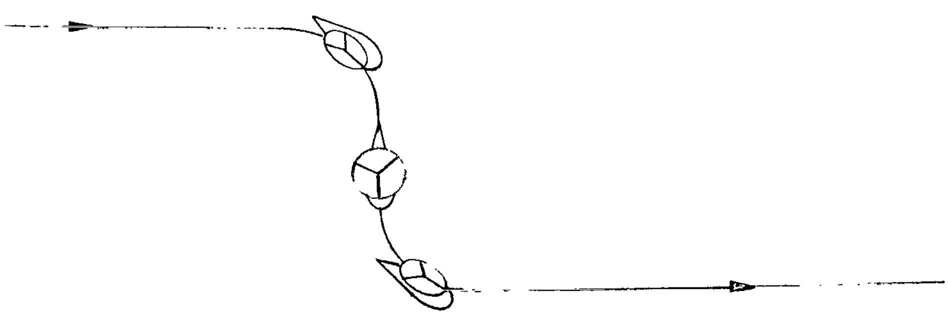
Figure 2.- Concluded.



(a) Slalom course (top view).

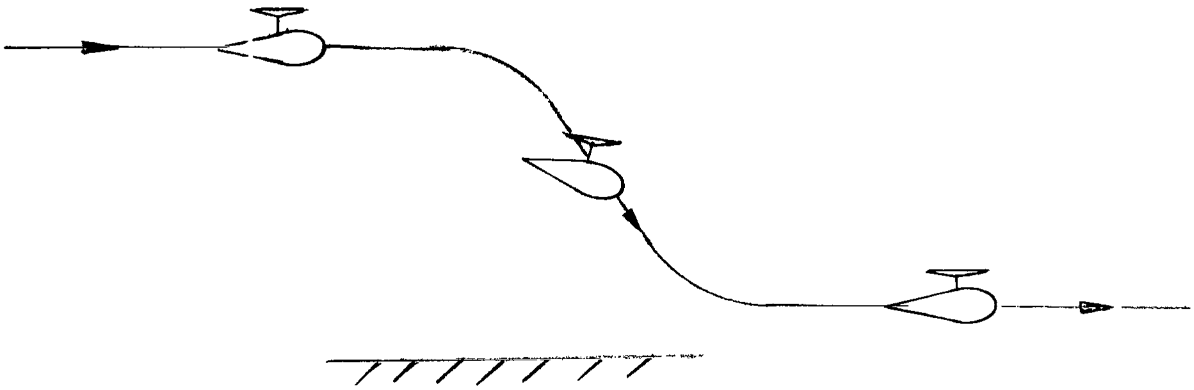


(b) Teardrop turn (top view).

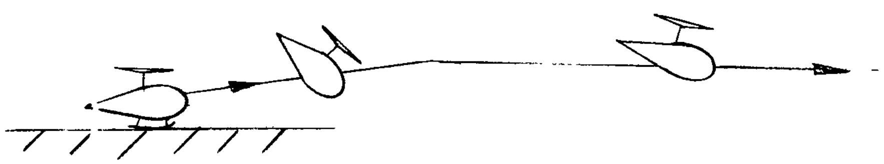


(c) S-turn (top view).

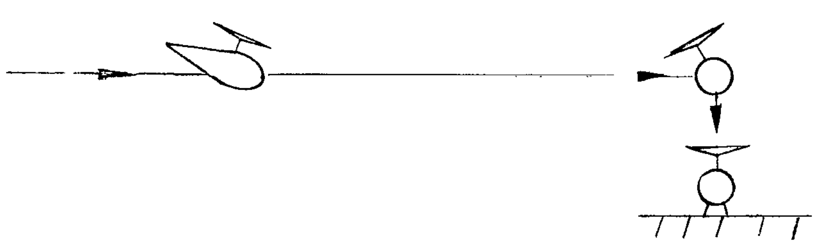
Figure 3.- Illustration of maneuver tasks.



(d) Hit-the-deck (side view).



(e) Scramble (side view).



(f) Whoa-boy (side view).

Figure 3.- Concluded.

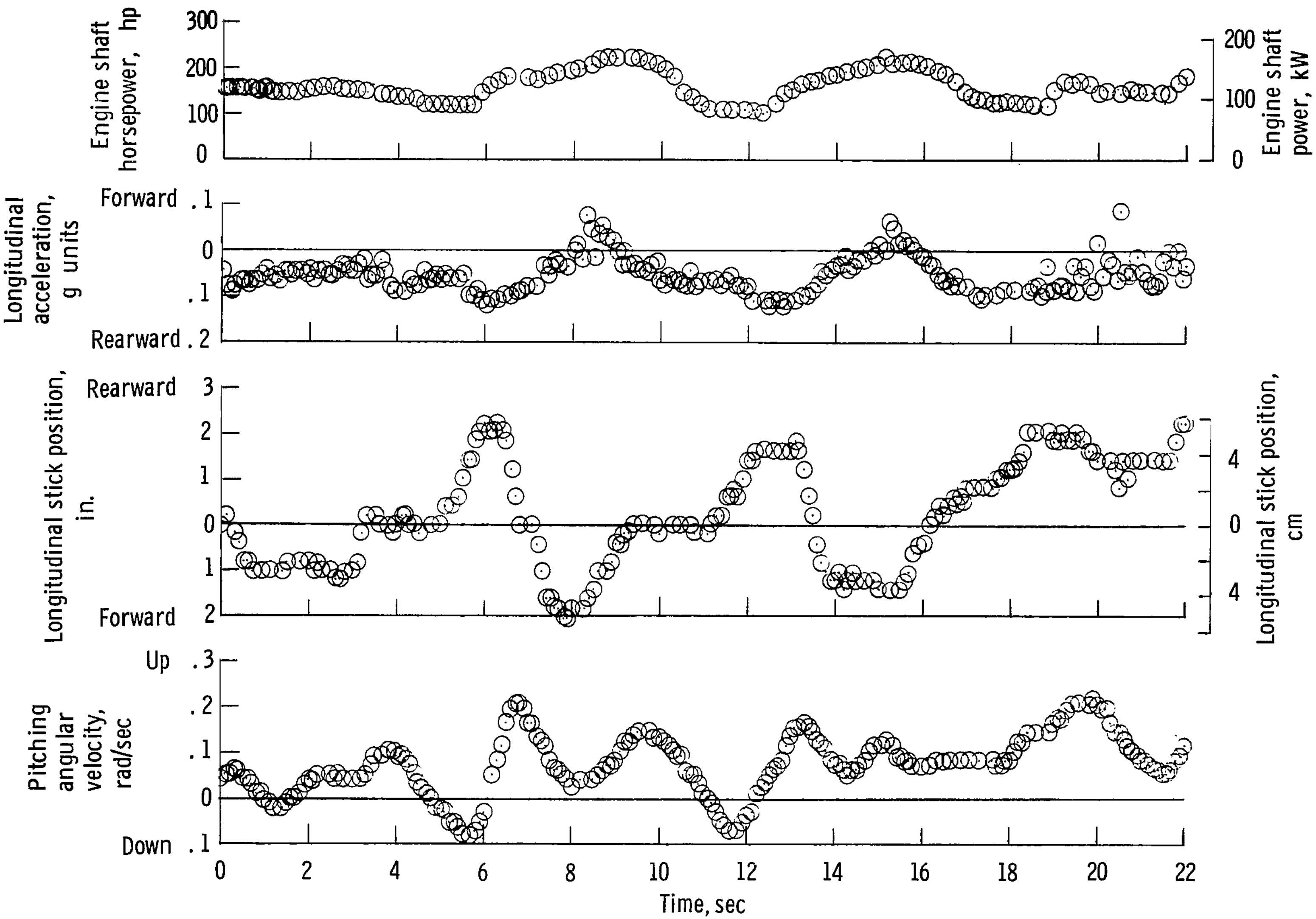


Figure 4.- Time histories of helicopter A maneuvering through slalom course with 400-foot (121.92-m) marker spacing.

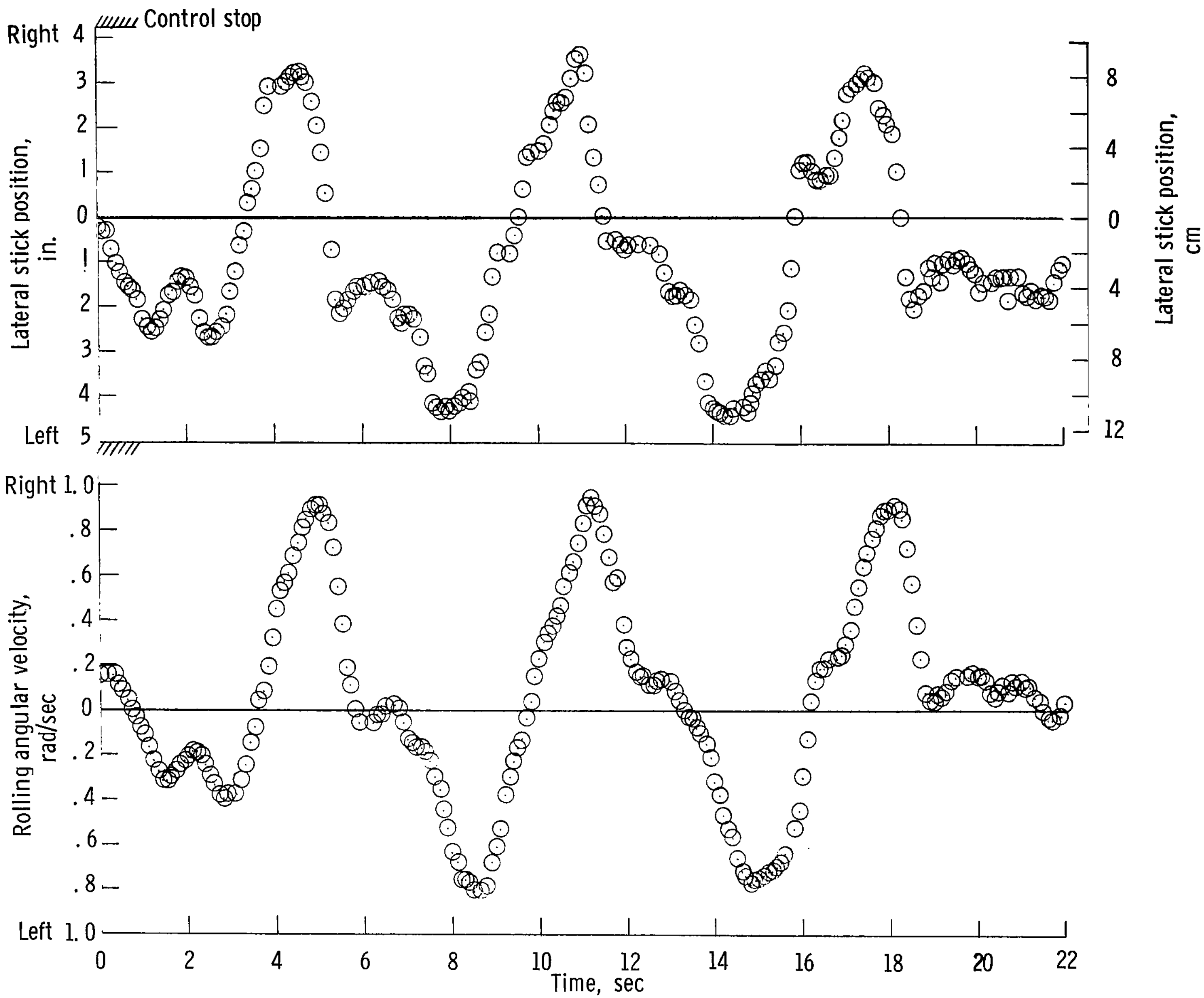


Figure 4.- Continued.

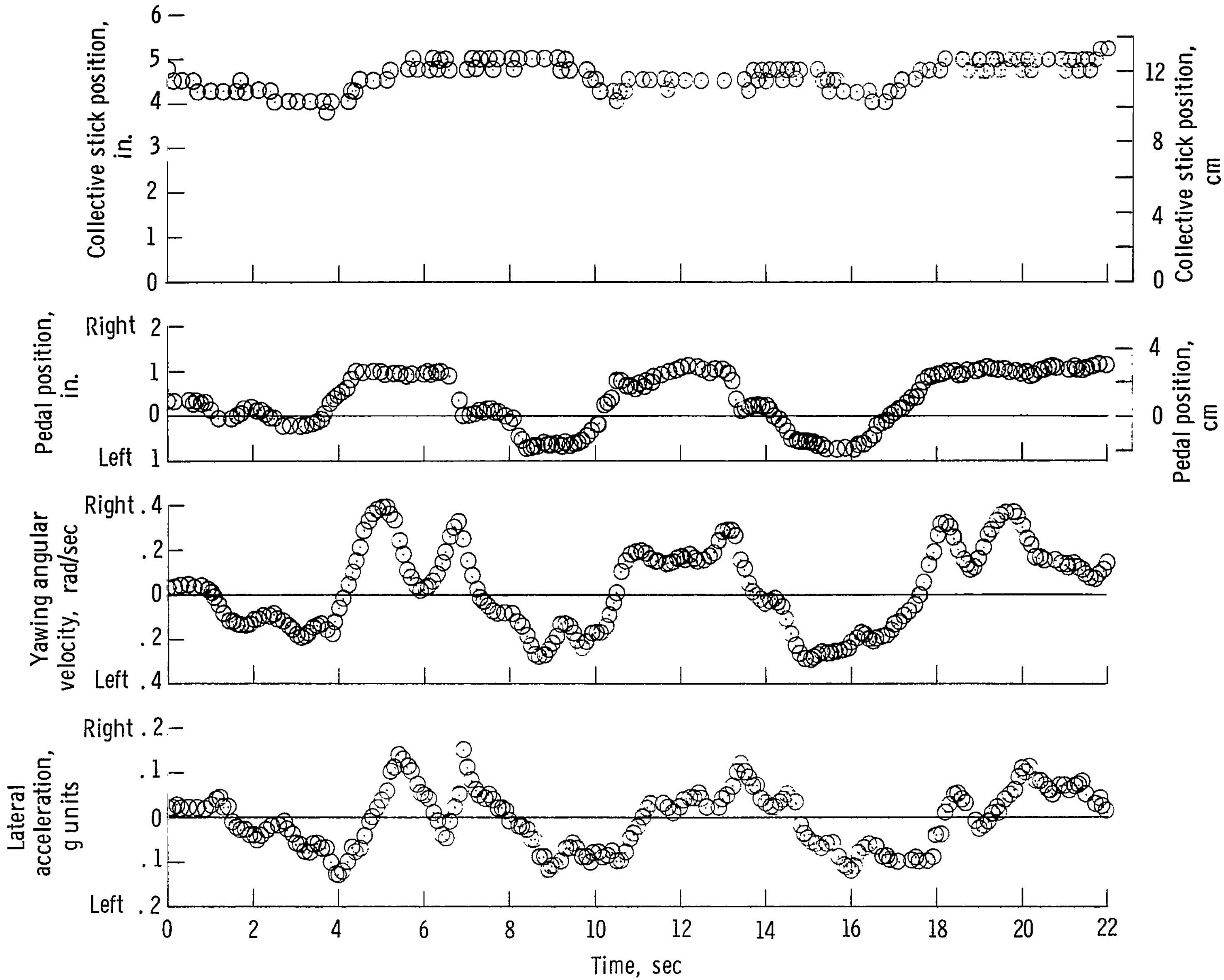


Figure 4.- Continued.

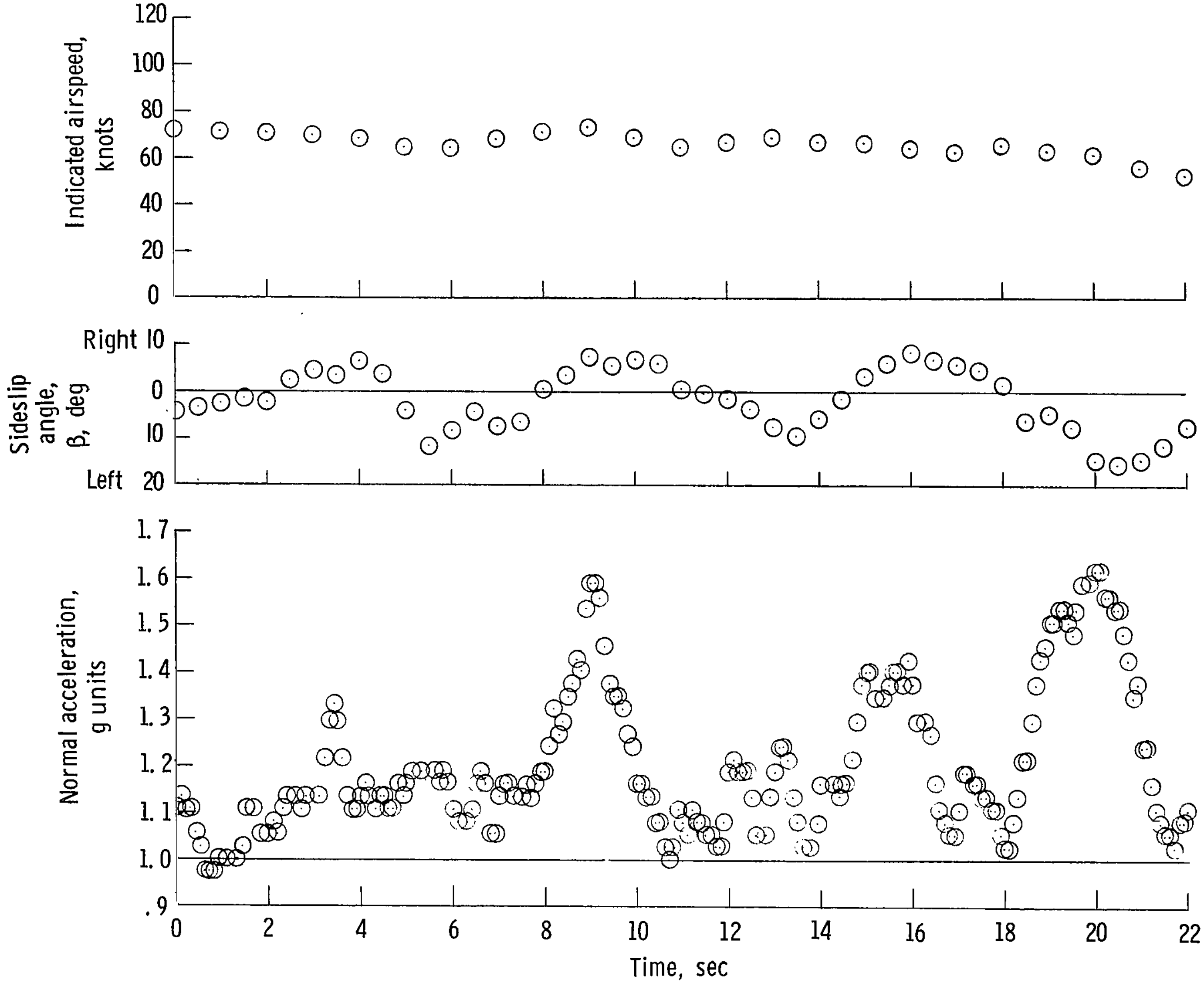


Figure 4.- Concluded.

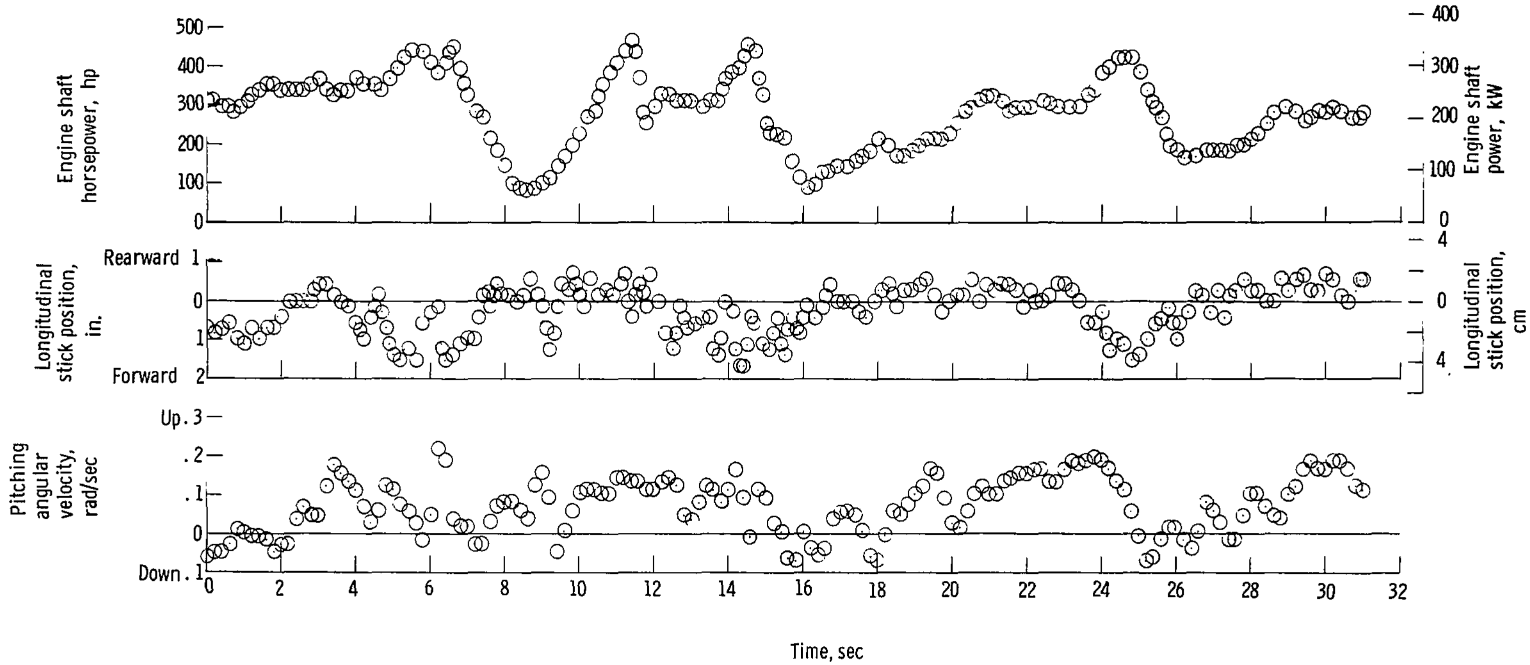


Figure 5.- Time histories of preliminary trials of helicopter B maneuvering through slalom course with 400-foot (121.92-m) marker spacing.

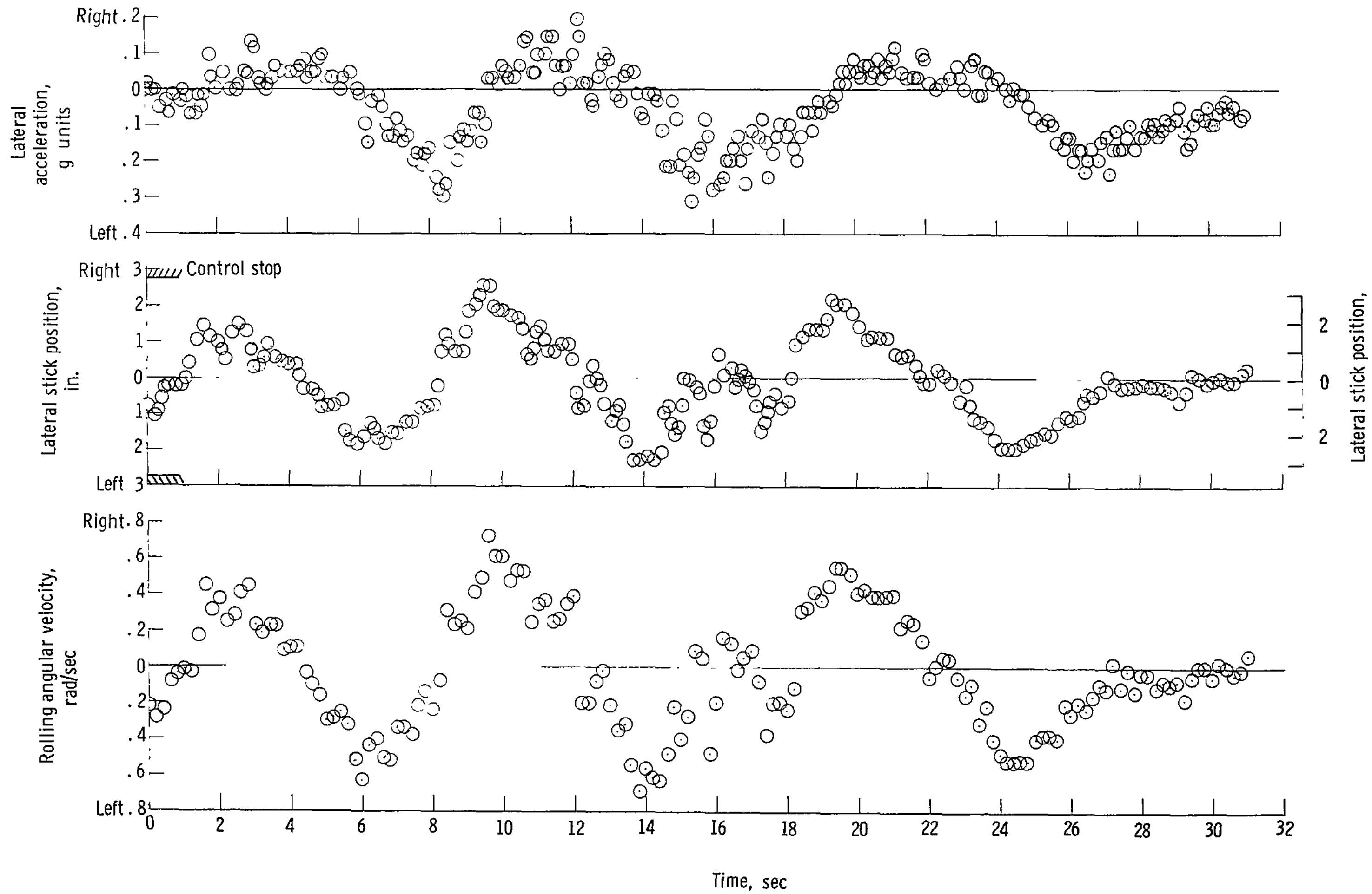


Figure 5.- Continued.

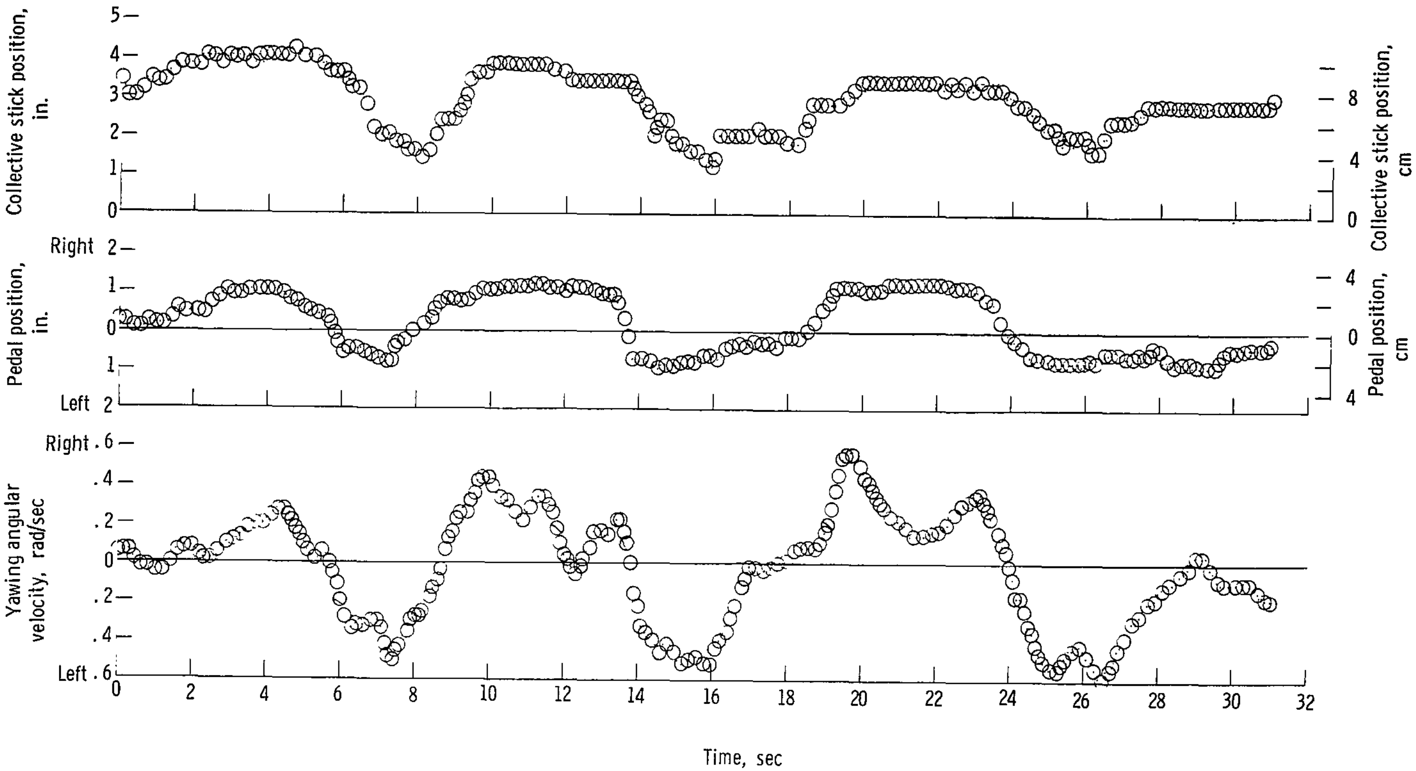


Figure 5.- Continued.

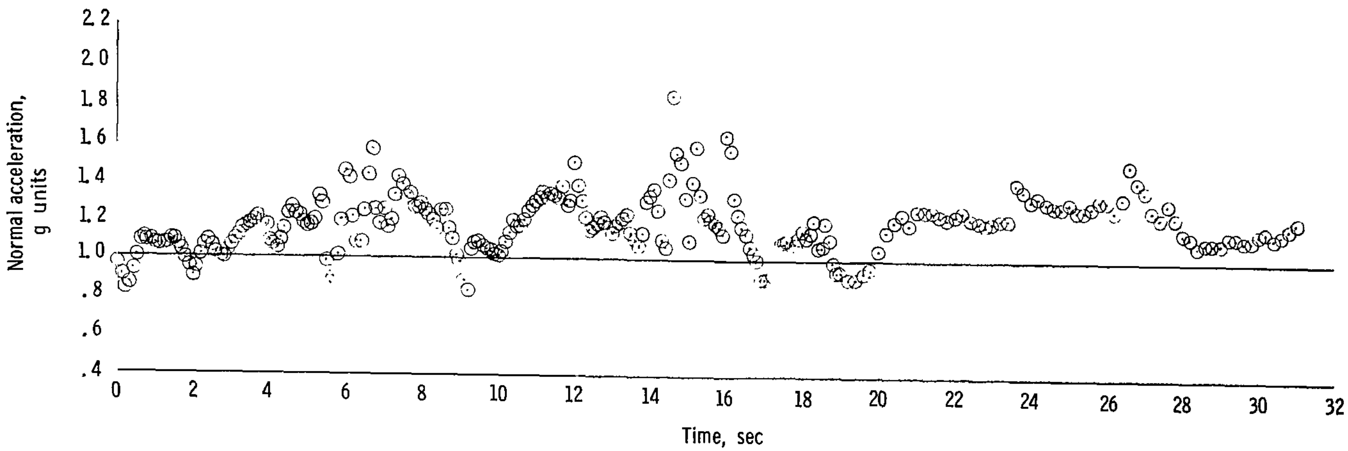


Figure 5.- Continued.

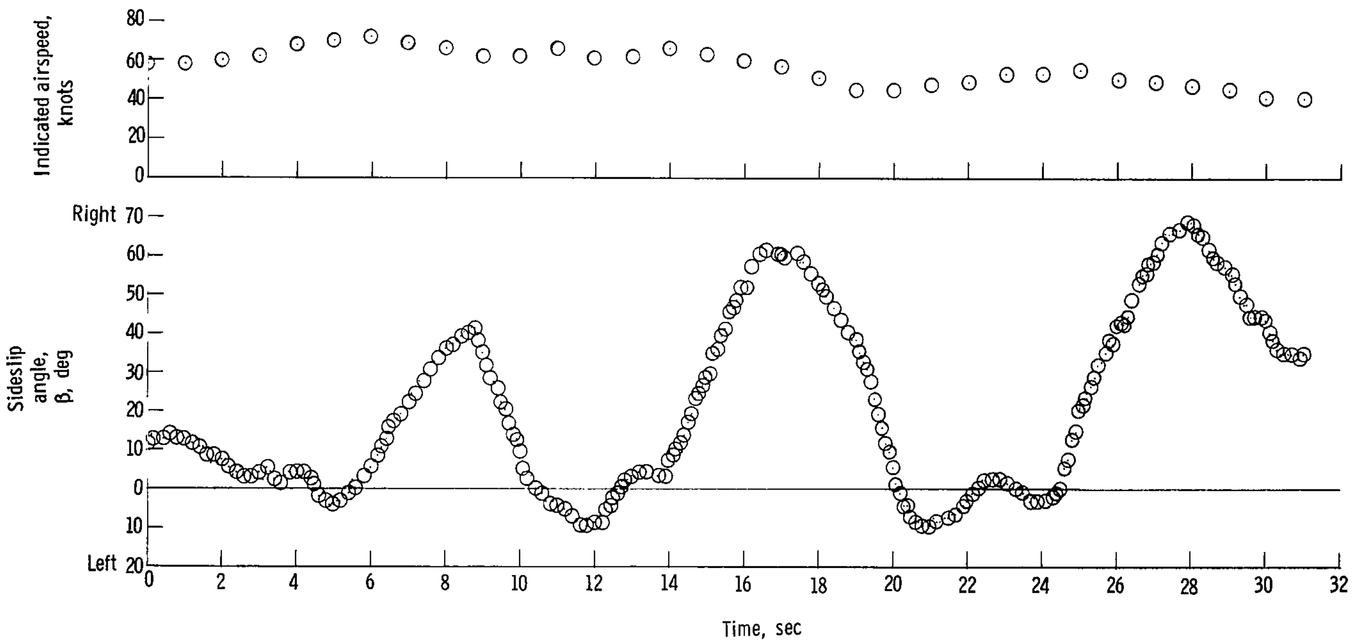


Figure 5.- Concluded.

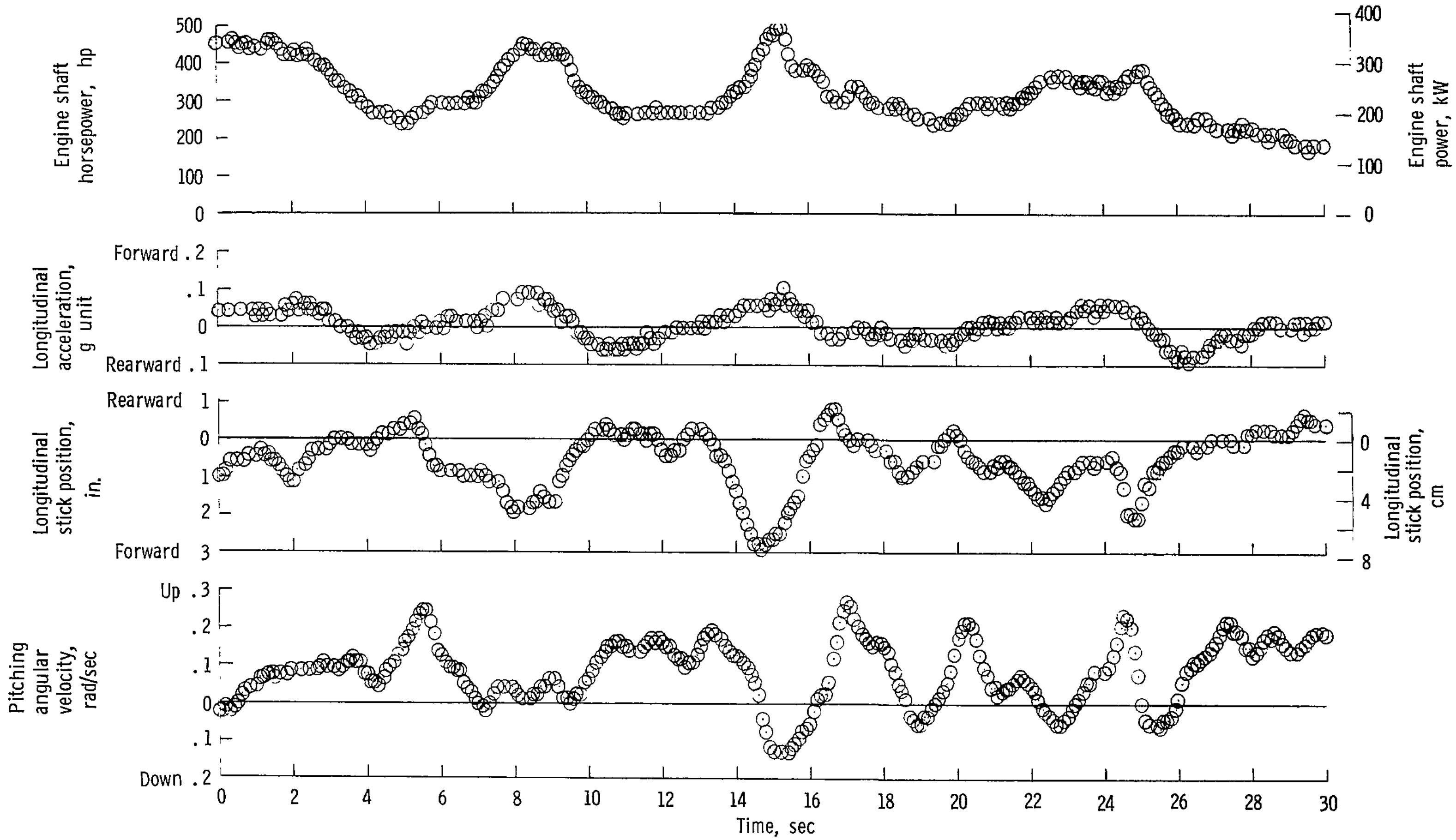


Figure 6.- Time histories of helicopter B maneuvering through simulated slalom course with collective control fixed. (In the interest of safety this task was simulated in that it was performed at a height above the ground of about 75 feet (22.86 m) without ground markers.)

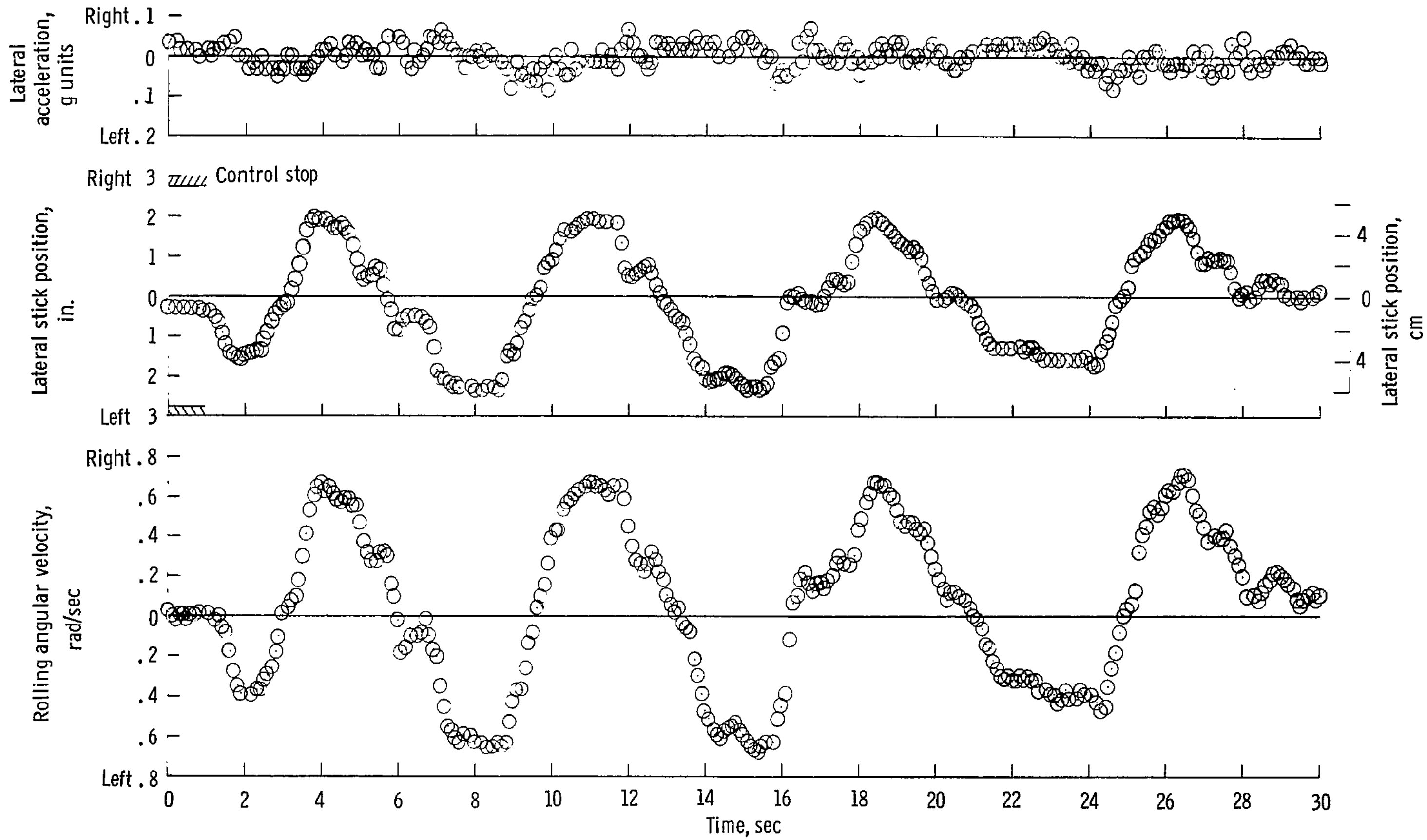
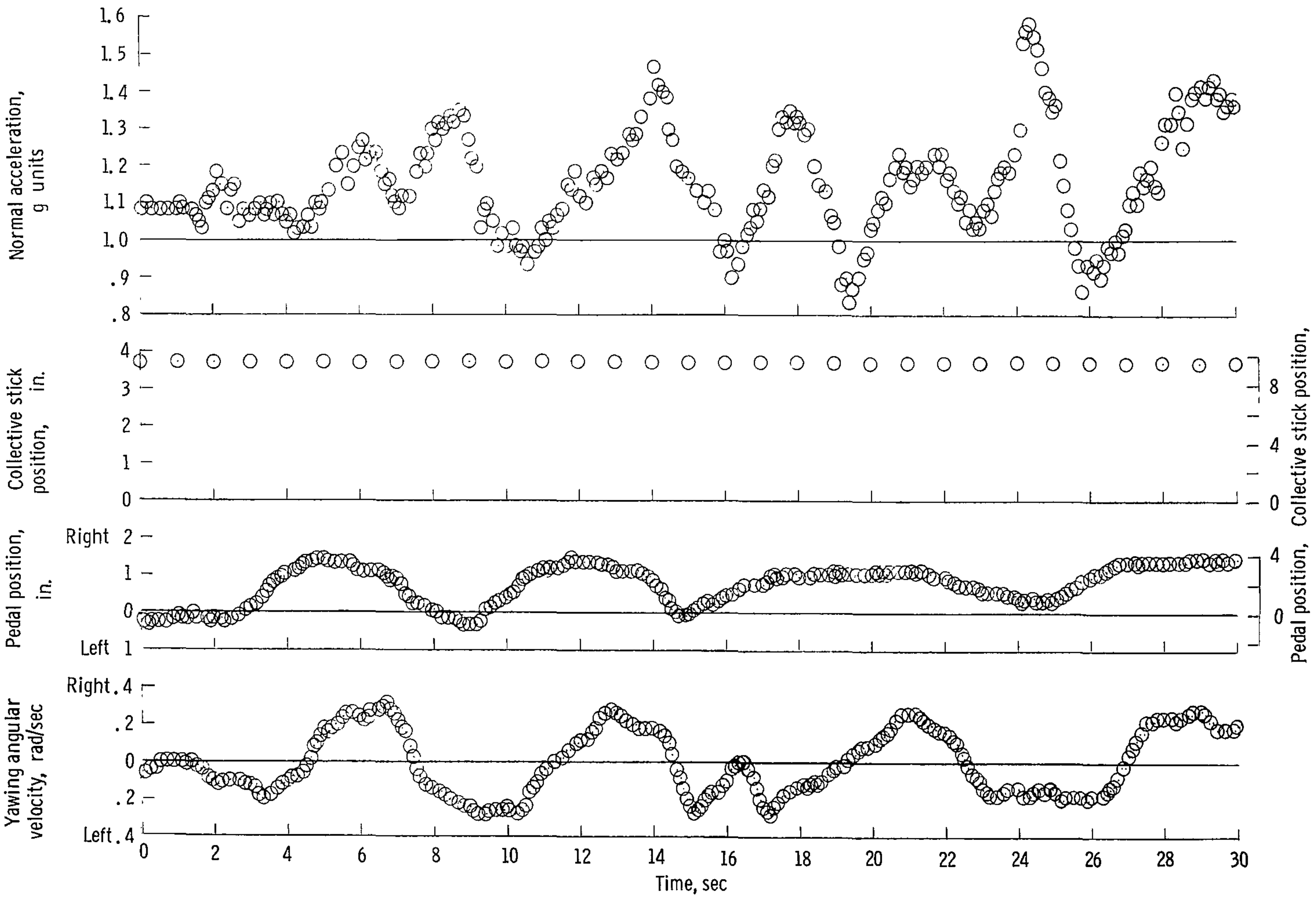


Figure 6.- Continued.



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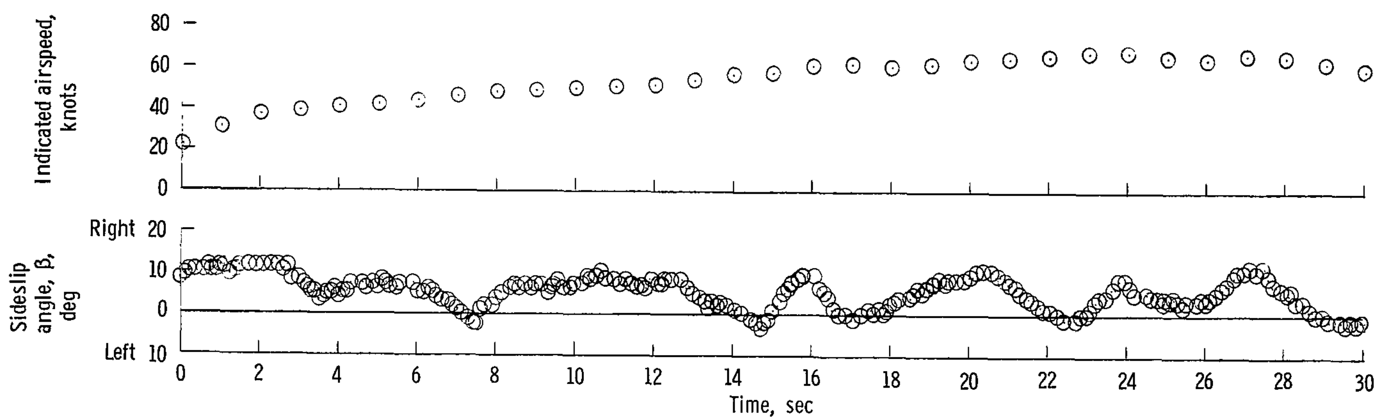


Figure 6.- Concluded.

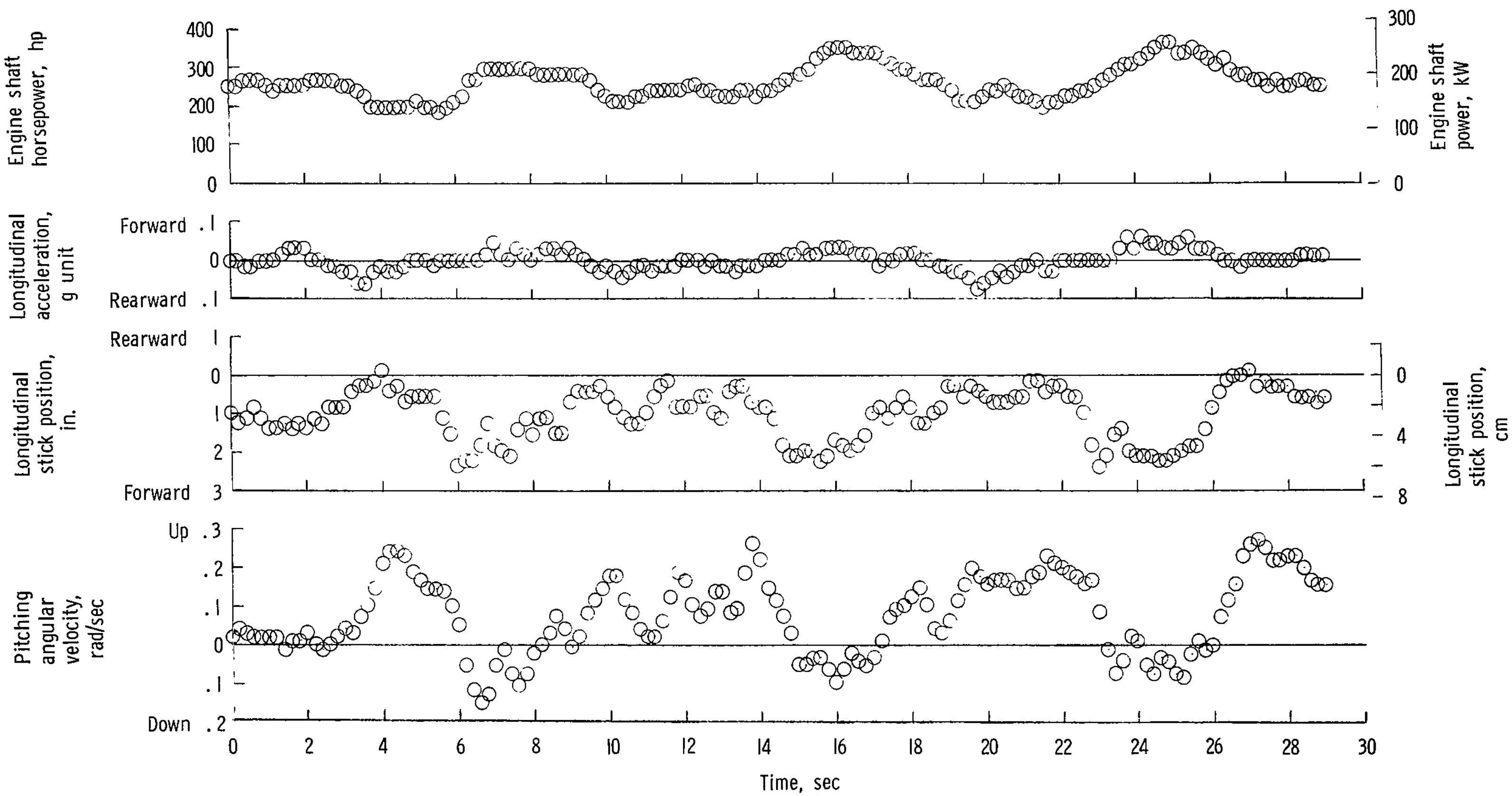


Figure 7.- Time histories of helicopter B maneuvering through slalom course with 400-foot (121.92-m) marker spacing (cab rigidly fixed to fuselage).

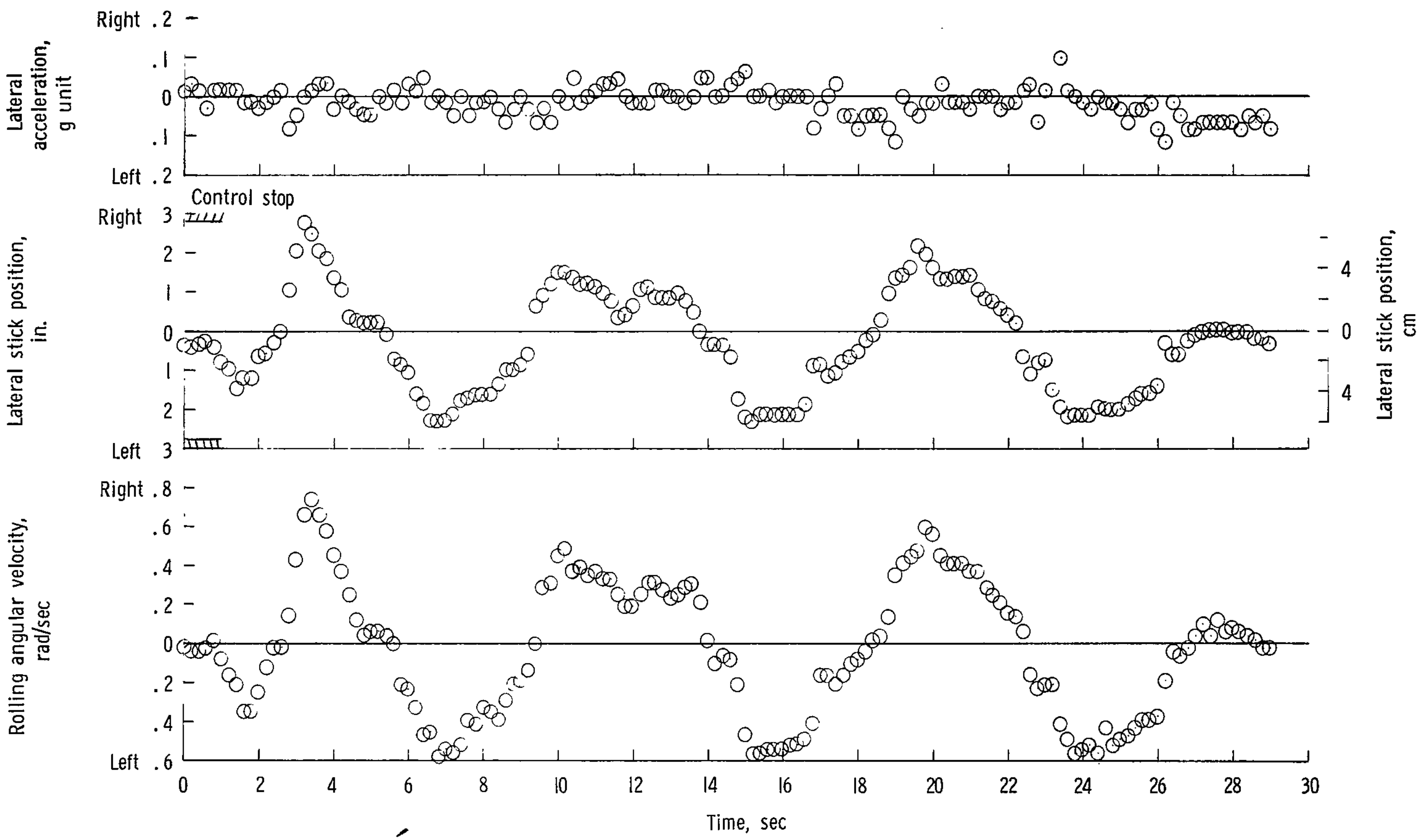


Figure 7.- Continued.

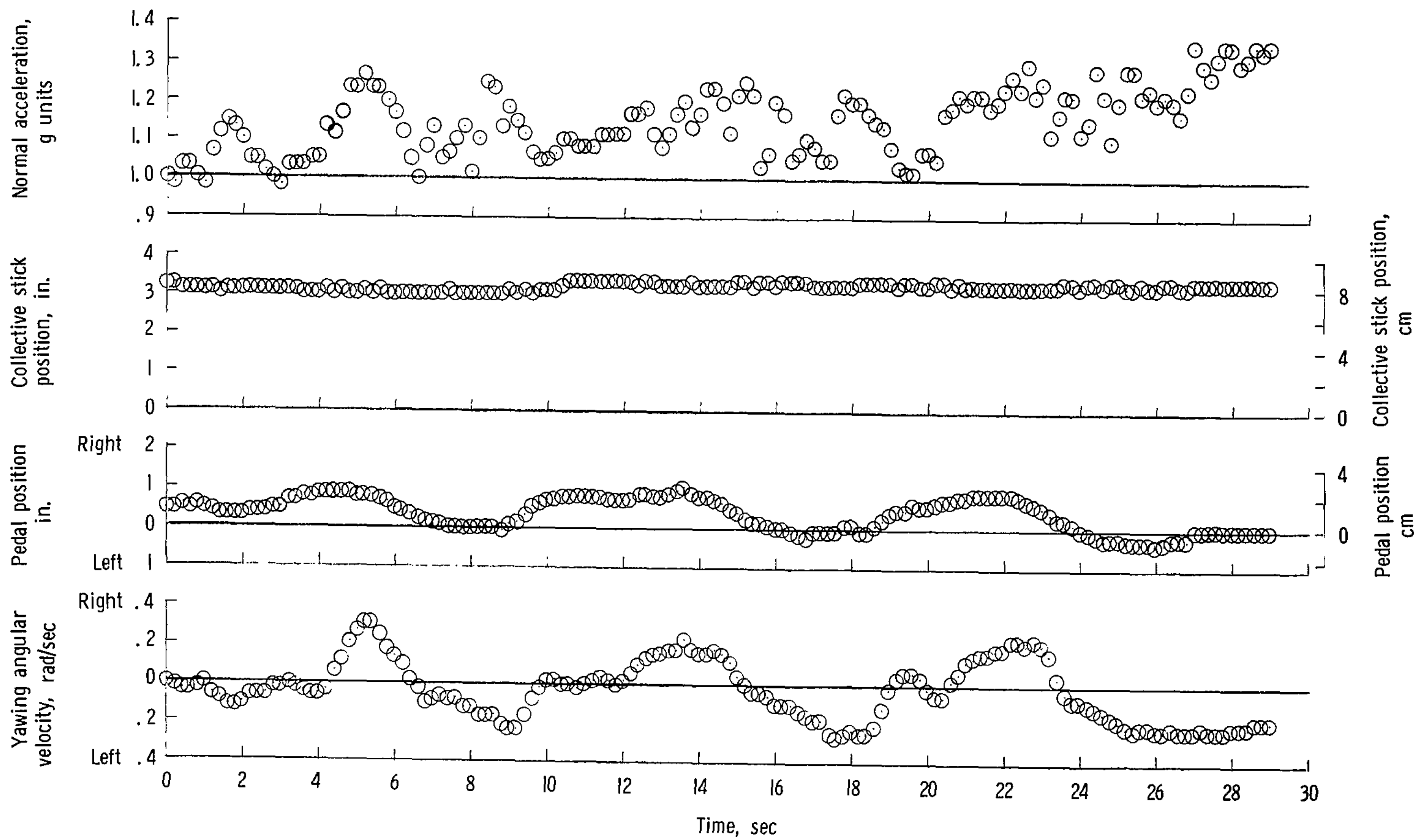


Figure 7.- Continued.

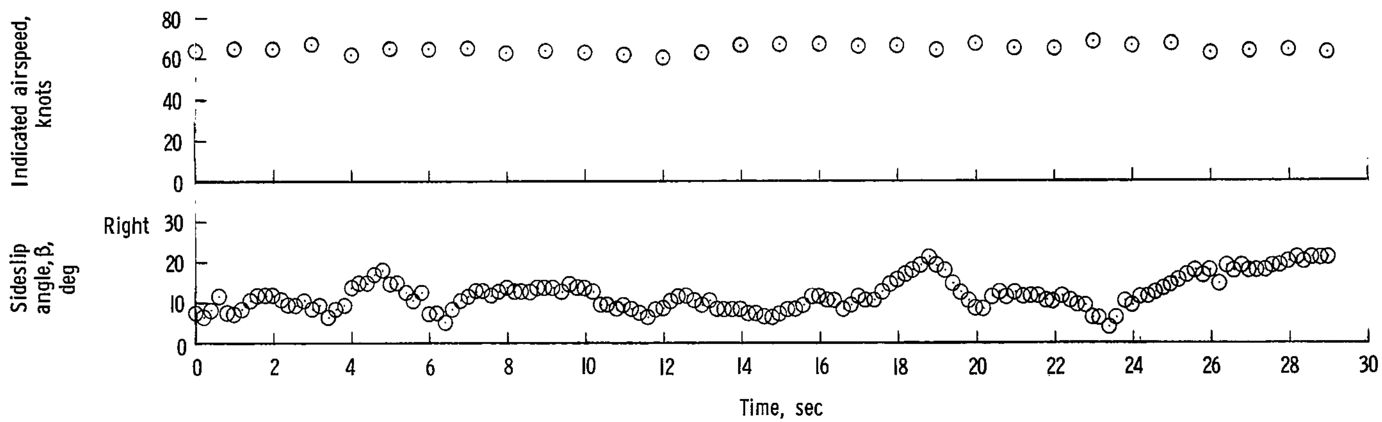


Figure 7.- Concluded.

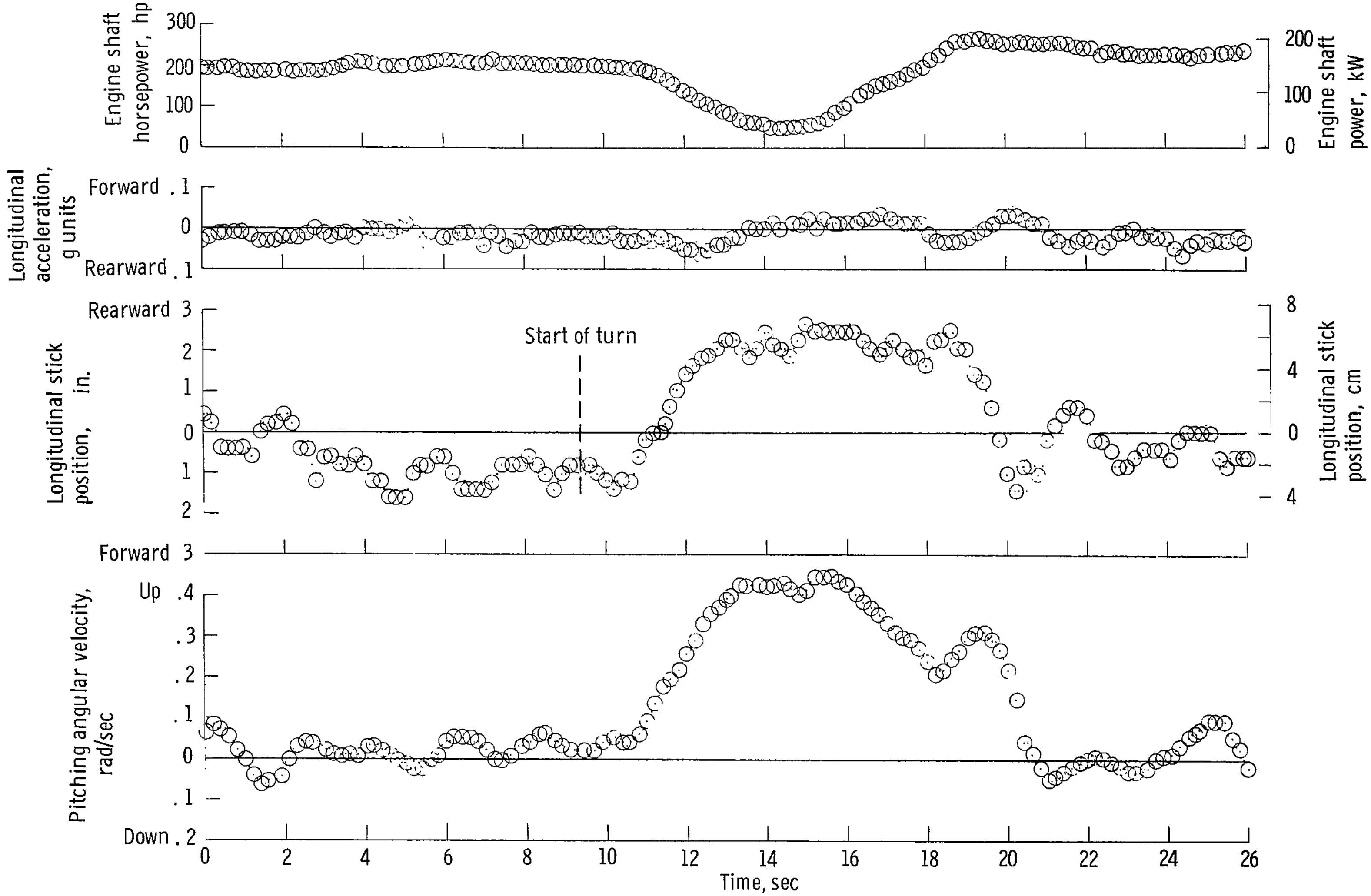


Figure 8.- Time histories of teardrop-turn maneuver performed by helicopter A.

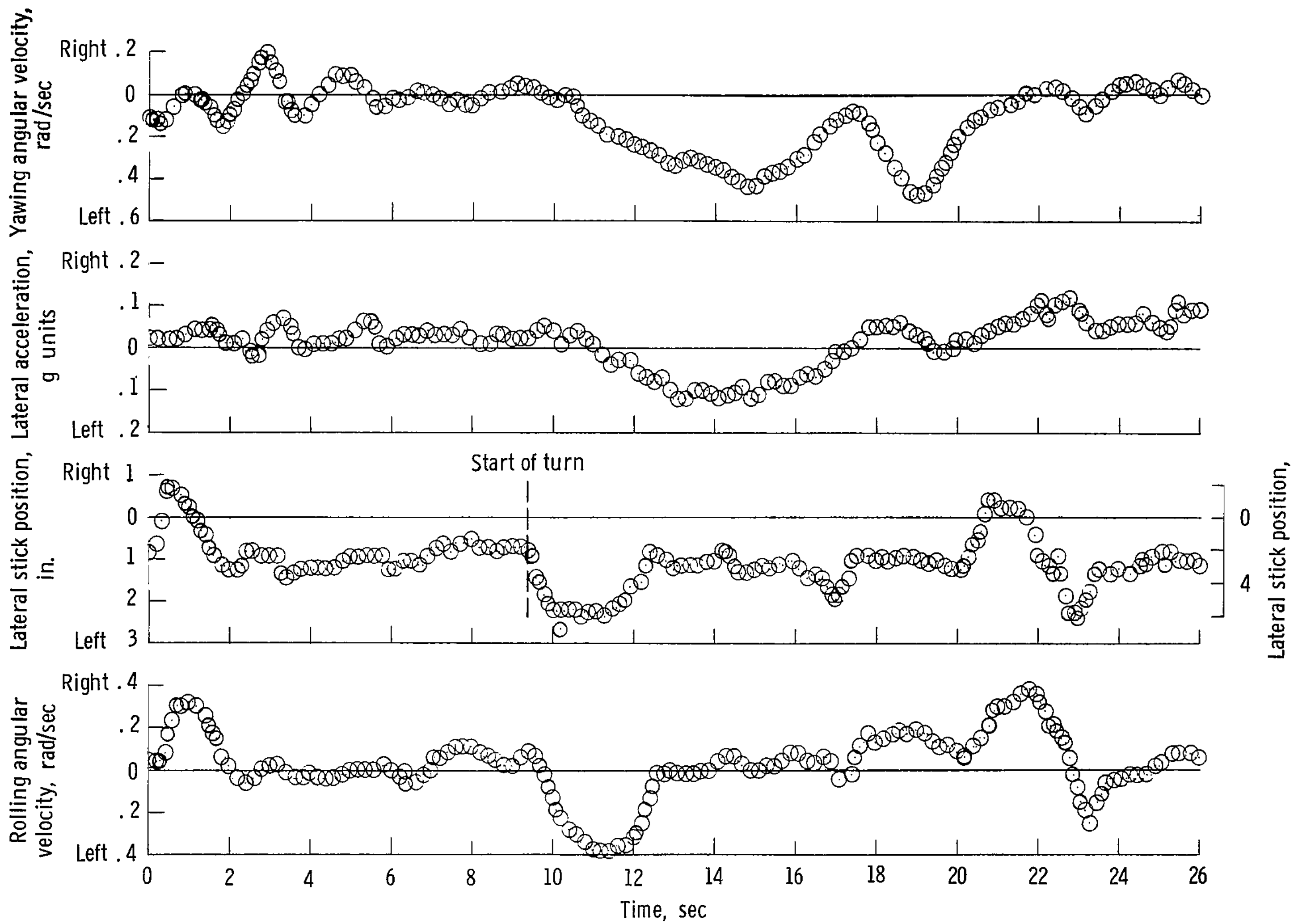
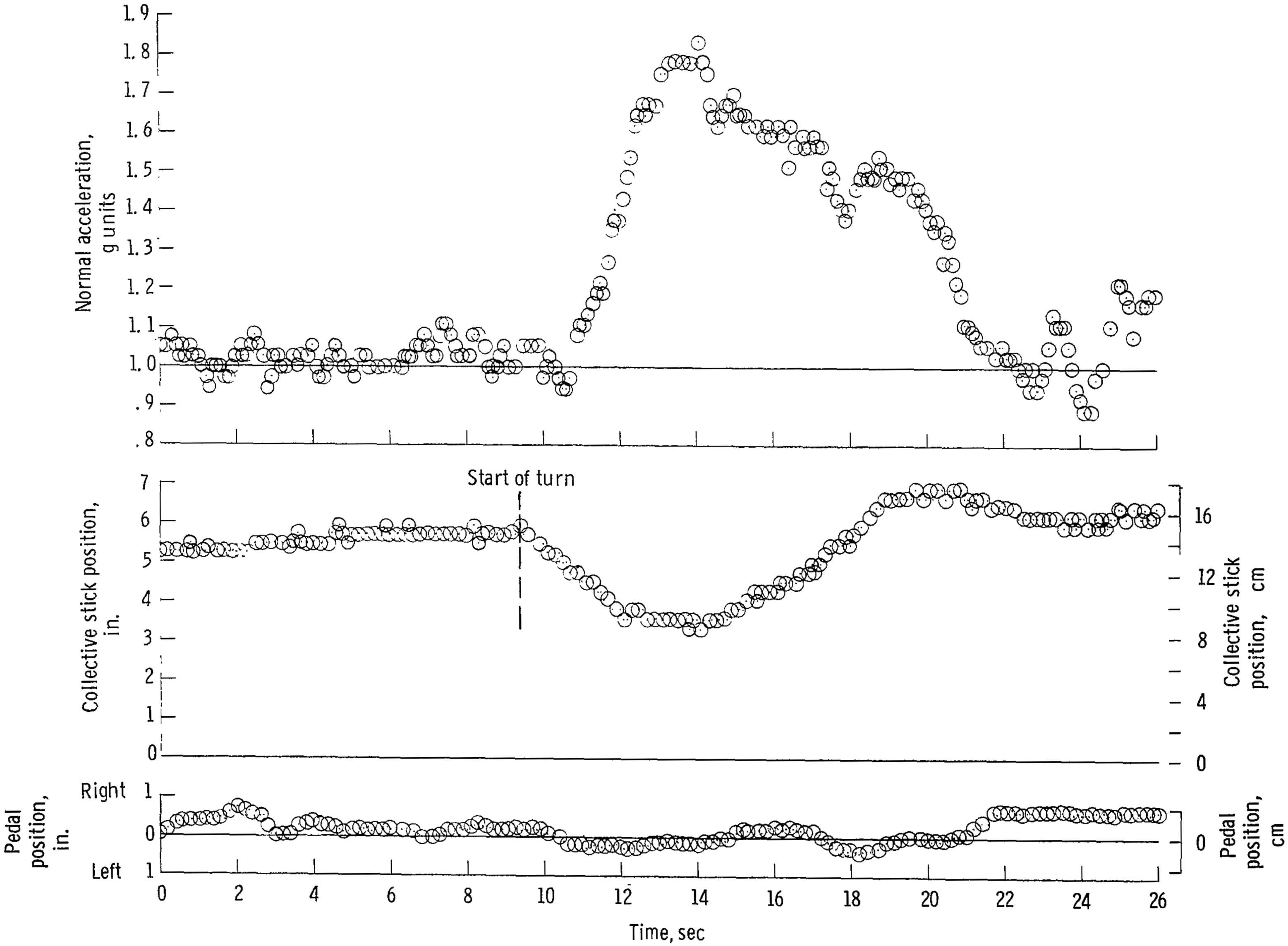


Figure 8.- Continued.



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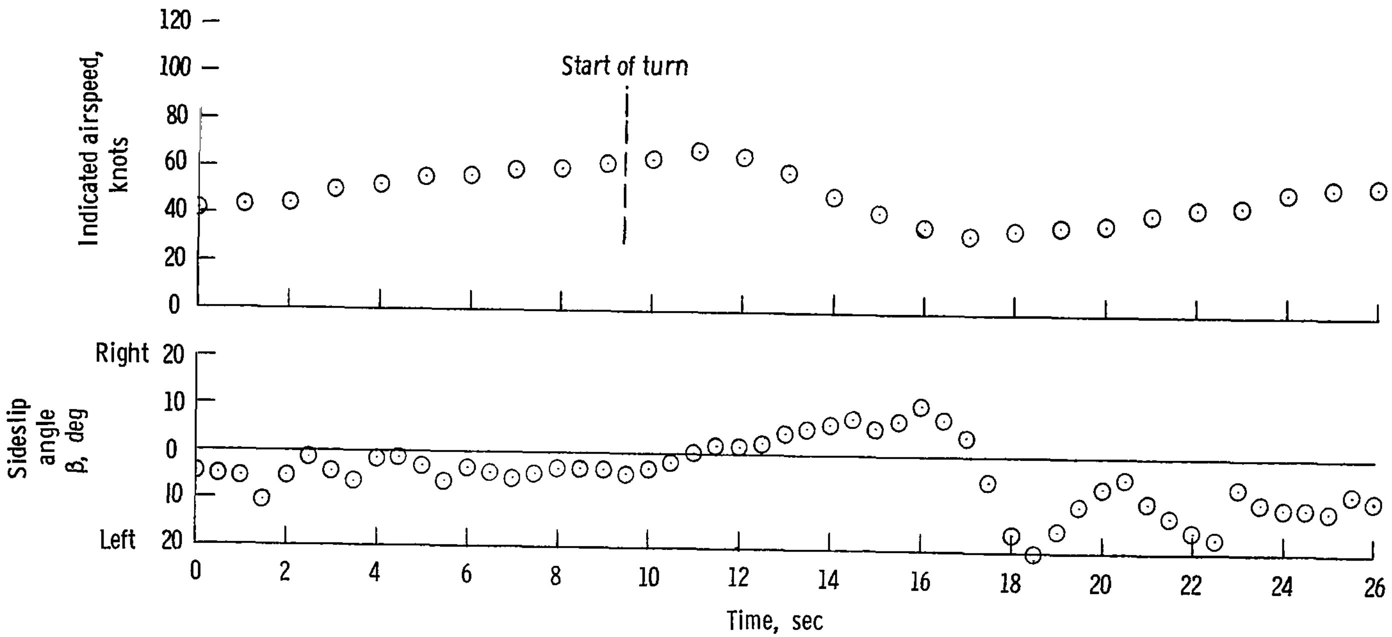

Figure 8.- Concluded.

Figure 9.- Maneuver stability characteristics of helicopter A at four trim-level-flight airspeeds.

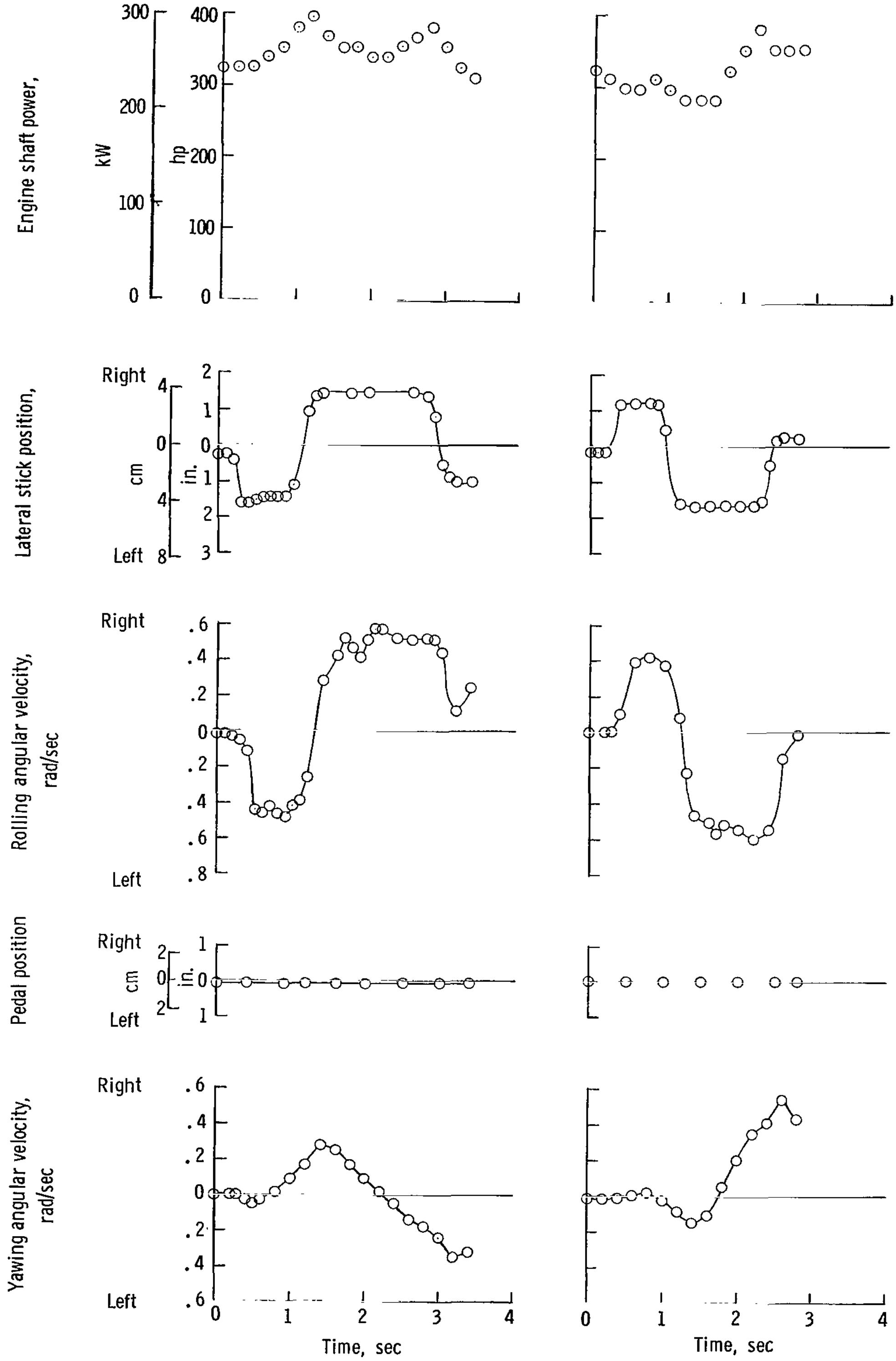

Figure 10.- Sample time histories of helicopter B showing adverse-yaw characteristics resulting from right and left roll maneuvers.